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Proses Kominusi Batubara Berdasarkan *Kinetic Energy Impact*

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Abstract

This research was conducted to analyze mathematically the distribution function of energy in the comminution process based on kinetic energy impact experiments with a 10 mm^{3}coal sample hitting the wall of the crusher, not being hit like a typical impact crusher. The analysis results prove that the equation $x_{maks} \propto x_{a_{maks}} \asymp f\Big|_{\left[\frac{\Delta x_{maks}}{\Delta(Vms)}\right]_{maks}}$, $x_{med} \propto x_{a_{med}} \asymp f\Big|_{\left[\frac{\Delta x_{med}}{\Delta(Vms)}\right]_{med}}$, $x_{min} \propto x_{a_{min}} \asymp f\Big|_{\left[\frac{\Delta x_{med}}{\Delta(Vms)}\right]_{min}}$ *is the distribution function of energy the comminution process energy that can be used to predict the energy requirements, and the particle size of coal fragmentation, and other brittle materials.*

Keywords*: Distribution, energy, comminution, kinetic, impact, coal.*

Abstrak

Penelitian ini dilakukan untuk menganalisis secara matematik dari *distribution function of energy* pada proses kominusi berdasarkan eksperimen *kinetic energy impact* dengan sampel batubara berukuran 10 mm^3 menghentam ke dinding penghancur, bukan dihentam seperti *crusher model impact* pada umumnya. Hasil analisis membuktikan bahwa persamaan $\mathrm{x_{maks}} \propto \mathrm{x_{a_{maks}}} \asymp f\Big|_{\left[\frac{\Delta \mathrm{x_{maks}}}{\Delta(\mathrm{Vms})}\right]_{\mathrm{maks}}}$, $\mathrm{x_{med}} \propto \mathrm{x_{a_{med}}} \asymp f\Big|_{\left[\frac{\Delta \mathrm{x_{med}}}{\Delta(\mathrm{Vms})}\right]_{\mathrm{med}}}$, $\mathrm{x_{min}} \propto \mathrm{x_{a_{min}}} \asymp f\Big|_{\left[\frac{\Delta \mathrm{x_{med}}}{\Delta(\mathrm{Vms})}\right]_{\mathrm{min}}}$ adalah *distribution function of energy* proses kominusi yang dapat digunakan untuk memprediksi kebutuhan *energy*, dan ukuran partikel dari fragmentasi batubara, dan material rapuh lainnya.

Kata kunci*: Distribusi, energi, kominusi, kinetik, impak, batubara.*

1. Pendahuluan

Hukum kominusi telah banyak dikembangkan oleh peneliti untuk memprediksi kebutuhan energi kominusi material rapuh melalui proses impact; dan hingga saat ini terus berkembang dengan berbagai model dan bentuk [1-7]. Proses kominusi dilakukan untuk merubah ukuran material rapuh menjadi lebih kecil [8]; proses ini berdasarkan kegagalan struktur material akibat impact [9, 10], dan dapat dilakukan secara bertingkat sesuai pengecilan ukuran yang diinginkan [11], serta dapat dianalisis secara matematik [12-14].

Pengurangan ukuran material rapuh melalui proses impact, memerlukan energi kominusi tertentu untuk terjadinya fragmentasi [15-18]; seperti menggunakan sistim pukulan dengan hammer [19, 20]. Langkah pentingnya adalah *fracture mechanic*, model perhitungan kebutuhan energi, dan produk ukuran partikel terhasil [21-31]. Berdasarkan hukum Rittinger, Bond dan Kick yang menyatakan bahwa kebutuhan energi pada proses kominusi material rapuh sistim impact, ditentukan oleh sifat dan distribusi ukuran awal material, serta kapasitas proses [32-34]. Proses ini juga berkaitan dengan hubungan antara fragments material terhadap penentuan awal energi impact [35, 36].

Untuk dapat memprediksi energi kominusi, mesti memperkirakan ukuran awal material, sudut impact, dan kecepatannya [37]. Sedangkan berdasarkan prinsip matematik fracture mechanic, proses kominusi pada material rapuh terjadi jika tekanan terhadap material dilakukan secara terus-menerus [38]. Dimana material rapuh memiliki sifat plastis kecil, penyerapan energi rendah sebelum terjadinya pecah; rambatan retak hampir searah dengan tekanan yang berlaku, serta distribusi pecahan sangat cepat [39]. Proses kominusi melalui prinsip fracture mechanic; perubahan pergerakan energi impact, perubahan ukuran, kecepatan momentum sebelum dan sesudah impact dapat diprediksi [40-43].

2. Metodologi

Eksperimen perubahan ukuran material menjadi lebih kecil sebagai proses kominusi, menandakan terjadinya distribusi energi impact pada material tersebut. Proses kominusi ini dilakukan dengan sampel batubara berukuran 10 mm^3. Model impact yang dilakukan adalah dengan memanfaatkan udara bertekanan dari dalam tabung sebesar 1bar hingga 3bar secara linier momentum.

Gambar 1. Ukuran fragments batubara

Sampel batubara menghentam ke dinding landasan penghancur dan pecah seperti ditunjukkan pada gambar 1, kemudian pecahan tersebut dianalisis sesuai prinsip hukum kominusi secara matematik.

3. Hasil dan Pembahasan

Distribusi kinetic energy impact $(\boldsymbol{x_a})$ pemecahan sampel disetiap 1mm3 bentuk kubus, dan disetiap 1mm3 kubus dengan pertambahan per 1mm sebagai fungsi jarak; persamaan distribusi energi kominusi seperti pada persamaan 1 hingga 6. Distribusi kinetic energy impact $(\boldsymbol{x_a})$ yang terjadi menunjukkan kominusi berfaktorkan volume $(\boldsymbol{V})$, massa $(\boldsymbol{m})$ dan ukuran partikel $(\boldsymbol{s})$ 1mm pertama; dimana kominusi telah berlaku disetiap 1mm jarak sepanjang 10mm, dari sampel yang telah lebih kecil dari ukuran awal. Kinetic energy impact pada setiap 1mm jarak sepanjang 10mm diwakili oleh $\boldsymbol{x_{a_1}} \rightarrow \boldsymbol{x_{a_{10}}}$. Sedangkan nilai dari $\boldsymbol{x_a}$ disetiap 1mm jarak berbeda sesuai nilai $\boldsymbol{V}$, $\boldsymbol{m}$ dan $\boldsymbol{s}$ setiap 1mm jarak partikel dari titik impact masing-masing; dan diwakili oleh $\boldsymbol{V_a}, \boldsymbol{m_a}, \boldsymbol{s_a} \rightarrow \boldsymbol{V_j}, \boldsymbol{m_j}, \boldsymbol{sz_j}$. Namun nilai $\boldsymbol{x_a}$ akan berubah jika perubahan faktor parameter $\boldsymbol{Vms}$ berlaku dari $(\boldsymbol{V_a}, \boldsymbol{m_a}, \boldsymbol{sz_a}) \rightarrow (\boldsymbol{V_a} + \boldsymbol{V_b} \rightarrow \boldsymbol{V_j}), (\boldsymbol{m_a} + \boldsymbol{m_b} \rightarrow \boldsymbol{m_j}), (\boldsymbol{s_a} + \boldsymbol{s_b} \rightarrow \boldsymbol{s_j})$. Maka persamaan nilai untuk distribusi kinetic energy impact $(\boldsymbol{x_a})$ adalah:

$$x_{a_1} = x\mathfrak{f}[|V_a \rightarrow |m_a \rightarrow |s_a] \qquad 1$$

$$x_{a_1} = x\mathfrak{f}[|V_b \rightarrow |m_b \rightarrow |s_b] \qquad 2$$

$$\int_{x_{a_1}}^{x_{a_{10}}} = x\mathfrak{f}|_{\left[\int_{V_a}^{V_j} \rightarrow \int_{m_a}^{m_j} \rightarrow \int_{s_a}^{s_j}\right]} \qquad 3$$

$$x_{a_1} = x\mathfrak{f}[|V_a \rightarrow |m_a \rightarrow |s_a] \qquad 4$$

$$x_{a_1 \rightarrow a_2} = x\mathfrak{f}_{\begin{bmatrix} |V_a + V_b \\ |m_a + m_b \\ |s_a + s_b \end{bmatrix}} \qquad 5$$

$$x_{a_1 \rightarrow a_{10}} = x\mathfrak{f}|_{\left[\left|\int_{V_a}^{V_j} + \left|\int_{m_a}^{m_j} + \left|\int_{s_a}^{s_j}\right]\right.\right.\right.} \qquad 6$$

Pada setiap $1mm \rightarrow 10mm$

Sentuhan Langsung: x_{a_1}

$$x_{V_a} = \frac{1}{2}mv^2\Big|_{10mm^3} \rightarrow x_{m_a} = \frac{1}{2}mv^2\Big|_{0.001\,kg} \rightarrow x_{sz_a} = \frac{1}{2}mv^2\Big|_{V_a} = \frac{1}{2}mv^2\Big|_1 \qquad 7$$

Gegaran 1: x_{a_2}

$$x_{V_b} = \frac{1}{2}mv^2\Big|_{10mm^3} \rightarrow x_{m_b} = \frac{1}{2}mv^2\Big|_{0.002\,kg} \rightarrow x_{sz_b} = \frac{1}{2}mv^2\Big|_{V_b} = \frac{1}{2}mv^2\Big|_2 \qquad 8$$

Gegaran 2: x_{a_3}

$$x_{V_c} = \frac{1}{2}mv^2\Big|_{10mm^3} \rightarrow x_{m_c} = \frac{1}{2}mv^2\Big|_{0.003\,kg} \rightarrow x_{sz_c} = \frac{1}{2}mv^2\Big|_{V_c} = \frac{1}{2}mv^2\Big|_3 \qquad 9$$

Gegaran 3: x_{a_4}

$$x_{V_d} = \frac{1}{2}mv^2\Big|_{10mm^3} \rightarrow x_{m_d} = \frac{1}{2}mv^2\Big|_{0.004\,kg} \rightarrow x_{sz_d} = \frac{1}{2}mv^2\Big|_{V_d} = \frac{1}{2}mv^2\Big|_4 \qquad 10$$

Gegaran 4: x_{a_5}

$$x_{V_e} = \frac{1}{2}mv^2\Big|_{10mm^3} \rightarrow x_{m_e} = \frac{1}{2}mv^2\Big|_{0.005\,kg} \rightarrow x_{sz_e} = \frac{1}{2}mv^2\Big|_{V_e} = \frac{1}{2}mv^2\Big|_5 \qquad 11$$

Gegaran 5: x_{a_6}

$$x_{V_f} = \frac{1}{2}mv^2\Big|_{10mm^3} \rightarrow x_{m_f} = \frac{1}{2}mv^2\Big|_{0.006\,kg} \rightarrow \qquad 12$$

$$x_{sz_f} = \frac{1}{2}mv^2\Big|_{V_f} = \frac{1}{2}mv^2\Big|_6$$

Gegaran 6: x_{a_7}

$$x_{V_g} = \frac{1}{2}mv^2\Big|_{10mm^3} \rightarrow x_{m_g} = \frac{1}{2}mv^2\Big|_{0.007\,kg} \rightarrow x_{sz_g} = \frac{1}{2}mv^2\Big|_{V_g} = \frac{1}{2}mv^2\Big|_7 \tag{13}$$

Gegaran 7: x_{a_8}

$$x_{V_h} = \frac{1}{2}mv^2\Big|_{10mm^3} \rightarrow x_{m_h} = \frac{1}{2}mv^2\Big|_{0.008\,kg} \rightarrow x_{sz_h} = \frac{1}{2}mv^2\Big|_{V_h} = \frac{1}{2}mv^2\Big|_8 \tag{14}$$

Gegaran 8: x_{a_9}

$$x_{V_i} = \frac{1}{2}mv^2\Big|_{10mm^3} \rightarrow x_{m_i} = \frac{1}{2}mv^2\Big|_{0.009\,kg} \rightarrow x_{sz_i} = \frac{1}{2}mv^2\Big|_{V_i} = \frac{1}{2}mv^2\Big|_9 \tag{15}$$

Gegaran 9: $x_{a_{10}}$

$$x_{V_j} = \frac{1}{2}mv^2\Big|_{10mm^3} \rightarrow x_{m_j} = \frac{1}{2}mv^2\Big|_{0.02\,kg} \rightarrow x_{sz_j} = \frac{1}{2}mv^2\Big|_{V_j} = \frac{1}{2}mv^2\Big|_{10} \tag{16}$$

Dimana x_{a_1} adalah impact sentuhan langsung x_a impact, $x_{a_2} \rightarrow x_{a_{10}}$ adalah gegarannya karena pertambahan disetiap 1mm hingga 10 mm, dan merupakan kominusi dengan fungsi jarak per 1mm berterusan pada sampel. Fungsi jarak dari titik impact berterusan sepanjang 10mm, menunjukkan hubungan antara titik hentaman terhadap jarak yang mempengaruhi nilai x_a. Sedangkan ukuran pecahan lebih besar jika semakin jauh dari titik pusat impact. Ini merupakan fragmentasi per 1mm jarak dari titik impact berterusan dengan fungsi jarak di sepanjang 10mm, dan memiliki hubungan dengan nilai x_a sampel.

Analisis perbandingan distribusi x_a pada kedudukan I, II, dan III dari kominusi menunjukkan hubungan energi kominusi terhadap fragmentasi dan ukuran partikel sampel. Pada x_a kedudukan I $\left(x_{a_{d_1}}\right)$ adalah kominusi terhadap pecahan dari sampel 10mm berawal dari $x_{a_1} \rightarrow V_a$, hingga $x_{a_{10}} \rightarrow V_j$. Kemudian x_a kedudukan II $\left(x_{a_{d_2}}\right)$ adalah kominusi terhadap pecahan dari sampel 10mm berawal dari $x_{a_1} \rightarrow V_a$, hingga $x_{a_{10}} \rightarrow V_j$. Sedangkan x_a kedudukan III $\left(x_{a_{d_3}}\right)$ adalah kominusi terhadap pecahan sampel 10 mm berawal dari $x_{a_1} \rightarrow x_{a_{10}}$, dengan persaman sebagai berikut:

Persamaan kedudukan I 17 hingga 71

$xa1 \rightarrow Va$	$xa1$=12mv2\|1mm31→$xa1$=12mv2\|1mm310
$xa2 \rightarrow Vb$	$xa2$=12mv2\|2mm31→$xa2$=12mv2\|2mm39
$xa3 \rightarrow Vc$	$xa3$=12mv2\|3mm31→$xa3$=12mv2\|3mm38
$xa4 \rightarrow Vd$	$xa4$=12mv2\|4mm31→$xa4$=12mv2\|4mm37
$xa5 \rightarrow Ve$	$xa5$=12mv2\|5mm31→$xa5$=12mv2\|5mm36
$xa6 \rightarrow Vf$	$xa6$=12mv2\|6mm31→$xa6$=12mv2\|6mm35
$xa7 \rightarrow Vg$	$xa7$=12mv2\|7mm31→$xa7$=12mv2\|7mm34
$xa8 \rightarrow Vh$	$xa8$=12mv2\|8mm31→$xa8$=12mv2\|8mm33
$xa9 \rightarrow Vi$	$xa9$=12mv2\|9mm31→$xa9$=12mv2\|9mm32
$xa10 \rightarrow Vj$	$xa10$=12mv2\|10mm31
Jumlah persamaan	55

Persamaan kedudukan II 72 hingga 162

$x_{a_1} \rightarrow x_{a_2}$	$x_{a_1} = \frac{1}{2}mv^2\|_{2mm^3}1 \rightarrow x_{a_1} = \frac{1}{2}mv^2\|_{2mm^3}10$
$x_{a_1} \rightarrow x_{a_2} \rightarrow x_{a_3}$	$x_{a_1} = \frac{1}{2}mv^2\|_{3mm^3}1 \rightarrow x_{a_1} = \frac{1}{2}mv^2\|_{2mm^3}10$
$x_{a_1} \rightarrow x_{a_2} \rightarrow x_{a_3} \rightarrow x_{a_4}$	$x_{a_1} = \frac{1}{2}mv^2\|_{4mm^3}1 \rightarrow x_{a_1} = \frac{1}{2}mv^2\|_{2mm^3}10$
$x_{a_1} \rightarrow x_{a_2} \rightarrow x_{a_3} \rightarrow x_{a_4} \rightarrow x_{a_5}$	$x_{a_1} = \frac{1}{2}mv^2\|_{5mm^3}1 \rightarrow x_{a_1} = \frac{1}{2}mv^2\|_{2mm^3}10$
$x_{a_1} \rightarrow x_{a_2} \rightarrow x_{a_3} \rightarrow x_{a_4} \rightarrow x_{a_5} \rightarrow x_{a_6}$	$x_{a_1} = \frac{1}{2}mv^2\|_{6mm^3}1 \rightarrow x_{a_1} = \frac{1}{2}mv^2\|_{2mm^3}10$
$x_{a_1} \rightarrow x_{a_2} \rightarrow x_{a_3} \rightarrow x_{a_4} \rightarrow x_{a_5} \rightarrow x_{a_6} \rightarrow x_{a_7}$	$x_{a_1} = \frac{1}{2}mv^2\|_{7mm^3}1 \rightarrow x_{a_1} = \frac{1}{2}mv^2\|_{2mm^3}10$
$x_{a_1} \rightarrow x_{a_2} \rightarrow x_{a_3} \rightarrow x_{a_4} \rightarrow x_{a_5} \rightarrow x_{a_6} \rightarrow x_{a_7} \rightarrow x_{a_8}$	$x_{a_1} = \frac{1}{2}mv^2\|_{8mm^3}1 \rightarrow x_{a_1} = \frac{1}{2}mv^2\|_{2mm^3}10$
$x_{a_1} \rightarrow x_{a_2} \rightarrow x_{a_3} \rightarrow x_{a_4} \rightarrow x_{a_5} \rightarrow x_{a_6} \rightarrow x_{a_7} \rightarrow x_{a_8} \rightarrow x_{a_9}$	$x_{a_1} = \frac{1}{2}mv^2\|_{9mm^3}1 \rightarrow x_{a_1} = \frac{1}{2}mv^2\|_{2mm^3}10$
$x_{a_1} \rightarrow x_{a_2} \rightarrow x_{a_3} \rightarrow x_{a_4} \rightarrow x_{a_5} \rightarrow x_{a_6} \rightarrow x_{a_7} \rightarrow x_{a_8} \rightarrow x_{a_9} \rightarrow x_{a_{10}}$	$x_{a_1} = \frac{1}{2}mv^2\|_{10mm^3}1 \rightarrow x_{a_1} = \frac{1}{2}mv^2\|_{2mm^3}10$
$x_{a_{10}} \rightarrow \infty$	$x_{a_1} = \frac{1}{2}mv^2\|_{10mm^3} \rightarrow \infty$ 1
Jumlah persamaan	91

Persamaan kedudukan III 163 hingga 217

	$x_{a_1} = \frac{1}{2}mv^2\vert_{1mm^3} \to x_{a_2}$
$x_{a_1} \to x_{a_2}$	$= \frac{1}{2}mv^2\vert_{2mm^3}1 \to x_{a_1}$
	$= \frac{1}{2}mv^2\vert_{2mm^3}10$
	$x_{a_1} = \frac{1}{2}mv^2\vert_{2mm^3} \to x_{a_3}$
$x_{a_1} \to x_{a_3}$	$= \frac{1}{2}mv^2\vert_{3mm^3}1 \to x_{a_1}$
	$= \frac{1}{2}mv^2\vert_{1mm^3}9$
	$x_{a_1} = \frac{1}{2}mv^2\vert_{3mm^3} \to x_{a_4}$
$x_{a_1} \to x_{a_4}$	$= \frac{1}{2}mv^2\vert_{4mm^3}1 \to x_{a_1}$
	$= \frac{1}{2}mv^2\vert_{1mm^3}8$
	$x_{a_1} = \frac{1}{2}mv^2\vert_{4mm^3} \to x_{a_5}$
$x_{a_1} \to x_{a_5}$	$= \frac{1}{2}mv^2\vert_{5mm^3}1 \to x_{a_1}$
	$= \frac{1}{2}mv^2\vert_{1mm^3}7$
	$x_{a_1} = \frac{1}{2}mv^2\vert_{5mm^3} \to x_{a_6}$
$x_{a_1} \to x_{a_6}$	$= \frac{1}{2}mv^2\vert_{6mm^3}1 \to x_{a_1}$
	$= \frac{1}{2}mv^2\vert_{1mm^3}6$
	$x_{a_1} = \frac{1}{2}mv^2\vert_{6mm^3} \to x_{a_7}$
$x_{a_1} \to x_{a_7}$	$= \frac{1}{2}mv^2\vert_{7mm^3}1 \to x_{a_1}$
	$= \frac{1}{2}mv^2\vert_{1mm^3}5$
	$x_{a_1} = \frac{1}{2}mv^2\vert_{7mm^3} \to x_{a_8}$
$x_{a_1} \to x_{a_8}$	$= \frac{1}{2}mv^2\vert_{8mm^3}1 \to x_{a_1}$
	$= \frac{1}{2}mv^2\vert_{1mm^3}4$
	$x_{a_1} = \frac{1}{2}mv^2\vert_{8mm^3} \to x_{a_9}$
$x_{a_1} \to x_{a_9}$	$= \frac{1}{2}mv^2\vert_{9mm^3}1 \to x_{a_1}$
	$= \frac{1}{2}mv^2\vert_{1mm^3}3$
	$x_{a_1} = \frac{1}{2}mv^2\vert_{9mm^3}$
$x_{a_1} \to x_{a_{10}}$	$\to x_{a_{10}} = \frac{1}{2}mv^2\vert_{10mm^3}1$
	$\to x_{a_1} = \frac{1}{2}mv^2\vert_{1mm^3}2$
$x_{a_{10}} \to \infty$	$x_{a_1} = \frac{1}{2}mv^2\vert_{1mm^3} \to \infty 1$
Jumlah persamaan	55

Berdasarkan persamaan 1 hingga persamaan 217, maka persamaan distribution function of energy proses kominusi sampel adalah:

$$\boldsymbol{x_{maks} \propto x_{a_{maks}} \asymp \mathfrak{f}\vert_{\left[\frac{\Delta x_{maks}}{\Delta(Vms)}\right]_{maks}}} \quad 218$$

$$\boldsymbol{x_{med} \propto x_{a_{med}} \asymp \mathfrak{f}\vert_{\left[\frac{\Delta x_{med}}{\Delta(Vms)}\right]_{med}}} \quad 219$$

$$\boldsymbol{x_{med} \propto x_{a_{min}} \asymp \mathfrak{f}\vert_{\left[\frac{\Delta x_{med}}{\Delta(Vms)}\right]_{min}}} \quad 220$$

Berdasarkan persamaan 218 hingga persamaan 220, maka secara matematik persamaan distribution function of energy proses kominusi pada sampel untuk memprediksi kebutuhan energi kominusi, dan ukuran partikel dari fragmentasi adalah: $x_{maks} \propto x_{a_{maks}} \asymp \mathfrak{f}\vert_{\left[\frac{\Delta x_{maks}}{\Delta(Vms)}\right]_{maks}}$ $, \propto x_{a_{med}} \asymp \mathfrak{f}\vert_{\left[\frac{\Delta x_{med}}{\Delta(Vms)}\right]_{med}}$ dan $x_{min} \propto x_{a_{min}} \asymp \mathfrak{f}\vert_{\left[\frac{\Delta x_{med}}{\Delta(Vms)}\right]_{min}}$.

4. Simpulan

Berdasarkan distribusi kinetic energy impact (x_a) pada material hasil eksperimen, secara matematik persamaan untuk distribution function of energy proses kominusi untuk memprediksi nilai energi dan ukuran partikel material adalah: $x_{maks} \propto x_{a_{maks}} \asymp \mathfrak{f}\vert_{\left[\frac{\Delta x_{maks}}{\Delta(Vms)}\right]_{maks}}$ $\propto x_{a_{med}}, x_{min} \propto x_{a_{min}} \asymp \mathfrak{f}\vert_{\left[\frac{\Delta x_{med}}{\Delta(Vms)}\right]_{min}}$

Daftar Pustaka

[1] Marcus Johansson (2017). *A Fundamental Model of an Industrial-Scale Jaw Crusher*. Minerals Engineering. Volume 105: 69-78.

[2] Gang Ma (2018). *The Effect of Different Fracture Mechanisms on Impact Fragmentation of Brittle Heterogeneous Solid*. International Journal of Impact Engineering. Volume 113: 132-143.

[3] Fatemeh Saeidi, Mohsen Yahyaei, and Malcolm Powell (2017). *Investigating the Effect of Applied Strain Rate in a Single Breakage Event*. Minerals Engineering. Volume 100: 211-222.

[4] Horiba Scientific (2016). *A Guidebook to Particle Size Analysis.* Horiba instruments Inc. 9755. Research Drive Irvine: CA 92618 USA 1-800-4.

[5] Wei-GangShen (2017). *Analysis of Impact Induced Rock Fragmentation Using a Discrete Element Approach.* International Journal of Rock Mechanics and Mining Sciences. Volume 98: 33-38.

[6] Alan T. Zehnder (2012). *Fracture Mechanics*. Volume 62: 978- 94-007-2594-2.

[7] Adriana Paluszny (2016). *A Direct Fragmentation Method with Weibull Function Distribution of Sizes Based on Finite- and Discrete Element Simulations*. International Journal of Solids and Structures. Volume 80: 38-51.

[8] Carina Ulsen (2018). *Concrete Aggregates Properties Crushed by Jaw and Impact Secondary Crushing*: Journal of Materials Research and Technology, JMRTE 381: 9-18.

[9] James D. Hogan (2015). *Dynamic Brittle Fragmentation: Probing the Byproducts of Hypervelocity Impact in Space*. Procedia Engineering. Volume 103: 205-212.

[10] X. F. Li (2018). *Dynamic Fragmentation of Rock Material: Characteristic Size, Fragment Distribution and Pulverization Law*. Engineering Fracture Mechanics. Volume 199: 739-759.

[11] C. M. Narayanan and B. C. Bhattacharyya (2014). *Mechanical Operations for Chemical Engineers.*India: Khana publishers.

[12] Juliana Segura-Salazar Gabriel (2017). *Mathematical Modeling of a Vertical Shaft Impact Crusherusing the whiten Model*. Minerals Engineering. Volume 111: 222-228.

[13] Weihong Li (2019). *Reducing Kominusi Over-Grinding of Powder Coatings with Modified GrindingPins in an Air Classifier Mill*. Powder Technology. Voume 344: 36-45.

[14] Chunshun Zhang, Giang D. Nguyen and Jayantha Kodikara (2016). *An Application of Breakage Mechanics for Predicting Energy–Size Reduction Relationships in Kominusi*. Powder Technology.Volume 287: 121-130.

[15] Li, X. F (2018). *Dynamic Fragmentation of Rock Material: Characteristic Size, Fragment Distribution and Pulverization Law.* Engineering Fracture Mechanics. Volume 199: 39-759.

[16] Tian xing Hou, Qiang XJu and ia-wen Zhou (2015). *Size Distribution, Morphology and Fractal Characteristics of Brittle Rock Fragmentations by the Impact Loading Effect.* Springer: Acta Mech 226:3623-3637.

[17] Fatemeh Saeidi, Mohsen Yahyaei, and Malcolm Powell (2017). *Investigating the Effect of Applied Strain Rate in a Single Breakage Event*. Minerals Engineering. Volume 100: 211-222.

[18] Horiba Scientific (2016). *A Guidebook to Particle Size Analysis.* Horiba instruments Inc. 9755.Research Drive Irvine: CA 92618 USA 1-800-4.

[19] Xuemin Liu (2016). *Calculation Model of Coal Kominusi Energy Consumption*. Minerals Engineering,Volume 92: 21-27.

[20] Barry A. Wills, James A. Finch FRSC and FCIM, P. Eng. (2016). *An Introduction to the Practical Aspects of Ore Treatment and Mineral*. Chapter 6 Crushers, Eighth Edition. Wills' Mineral Processing Technology. Recovery: Elsevier: 126-146.

[21] Zhang Xingang (2019). *Model Smoothing Method of Contact-Impact Dynamics in Flexible Multibody Systems.* Mechanism and Machine Theory. Volume 138: 124-148.

[22] Bereket Yohannes and Xue Liu (2018). *Particle Size Induced Heterogeneity in Compacted Powders: Effect of Large Particles.* Advanced Powder Technology. Volume 29: 2978-2986.

[23] Jaw Crusher (2016). *Mineral Processing Design and Operations.* Second Edition, an Introduction: 123-152.

[24] Avi Uzi and Avi Levy (2018). *Energy Absorption by the Particle and the Surface during Impact*. Wear.Volumes 404-405: 92-110.

[25] Weining Xie, Yaqun He and Lili Qu (2018). *Effect of Particle Properties on the Energy-Size Reductionof Coal in the Ball-and-Race Mill.* Powder Technology. Volume 333: 404-409.

[26] Sudarshan Martins (2016). *Size-Energy Relationship in Kominusi, Incorporating Scaling Laws and Heat*. International Journal of Mineral Processing. Volume 153: 29-43.

[27] Jiayuan Luo, Gun Huang and Long Zhang (2018). *Micro Shape of Coal Particle and Crushing Energy.*International Journal of Mining Science and Technology. Volume 28: 1009-1014.

[28] Yongfu Xu (2018). *The Fractal Evolution of Particle Fragmentation under Different Fracture Energy.*Powder Technology. Volume 323: 337-345.

[29] Tian-xing Hou, Qiang Xu and Xing-guo Yang · (2015). *Experimental Study of the*

FragmentationCharacteristics of Brittle Rocks by the Effect of a Free-Fall Round Hammer. International JournalFracture. Volume 194: 169-185.

[30] WeiLi Tristan, J. Delaney and Xiangmin Jiao1 (2016). *Finite Element Model for Brittle Fracture andFragmentation*. Procedia Computer Science. Volume 80: 245-256.

[31] Li Xuefeng, Wang Shibo and Ge Shirong (2018). *Investigation on the Influence Mechanism of Rock Brittleness on Rock Fragmentation and Cutting Performance by Discrete Element Method*.Measurement. Volume 113: 120-130.

[32] Martin J. Rhodes (2008). *Introduction to Particle Technology.* 2nd Edition. John Wiley and Sons, Ltd: ISBN 9780470014271.

[33] Georg Unland (2007). *The Principles of Single-Particle Crushing*. Handbook of Powder Technology. Germany, Elsevier: Volume 12.

[34] Fuzuli Agrı Akcay (2018). *Theoretical Prediction of Fracture of Initially Crack-Free Brittle Materials.*Procedia Structural Integrity. Volume 13: 1695-1701.

[35] Jiayuan Luo, Gun Huang and Long Zhang (2018). *Micro Shape of Coal Particle and Crushing Energy.*International Journal of Mining Science and Technology. Volume 28: 1009-1014.

[36] Zhang and Zongxian (2017). *Kinetic Energy and its Applications in Mining Engineering.* International Journal of Mining Science and Technology. Volume 27: 237-244.

[37] Tobias Hoertha and Frank Schäfera (2015). *Momentum Transfer in Hypervelocity Impact Experimentson Rock Targets.* Procardia Engineering. Volume 103: 197-204.

[38] Brian Law (1993). *Fracture of Brittle Solids*. Second Edition. A Cambridge University Press: ISBN 0521 40972 1.

[39] J. W. Morris, Jr (2002). *Materials Science: Defects in Crystals.* Berkley: University of California at Berkeley.

[40] Min Seok Choi and Jin Won Lee (2015). *Characteristics of Kinetic Energy Transfer in Collisions between a Fragile Nano-Particle and a Rigid Particle on a Surface.* Journal of Aerosol Science.Volume 84: 1-8.

[41] Zhang Dongmei (2017). *Study on Collision of Threaded Connection during Impact.* InternationalJournal of Impact Engineering. Volume 106: 133-145.

[42] Fatemeh Saeidi (2016). *A henomenological Model of Single Particle Breakage as A Multi-Stage Process.* Minerals Engineering. Volume 98: 90-100.

[43] C. Z. Tan (2018). *Wave Equation for the Energy and the Momentum of a Moving Particle.* Optik.Volume 168: 864-872.