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The dependance of breakage energy on the grain size for selected biomaterials

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Abstract. The aim of this research is to expand the knowledge on the description of the grains breakage energy. In effect of the research a model to describe the rice and corn grains breakage energy in dependance of size was developed. This was achieved by linking the level of grinding energy with the properties of the material (particle size) and the loading conditions. The selected grains (rice and corn) were subjected to loads (compression and cutting) on a testing machine. Based on the force-displacement curves, the relationship between the energy necessary to cause a breakage and particle size was described. The results show, that the energy needed for grain shearing changes with the particle size according to the power law, similarly to brittle materials. Through proposed modeling approach, it will be possible to reduce undesirable grain damage as well as improve the operation and design of processing machines in terms of their energy consumption and efficiency.

1. Introduction

The grain breakage is common process, which could be controlled and intentional in processing operations, such as comminution, extraction, etc. [1–4] or uncontrolled and unintentional causing losses and decrease in grain quality [5]. To initiate the breakage usually the portion of energy is needed and the knowledge about that, how material will behave under specific load is crucial to model and predict the breakage [6–8].

As the previous research shows, the breakage energy depends on the materials properties such as: size, humidity, strengths, hardness harvest time [9,10]. In the study [10], it was found on the example of wheat, that the energy needed for grain shearing increase with the grain mass and vitreousity increase. The study [10] also indicates that the temperature of the grain cause changes in the specific energy for grain sharing – the energy increase when the grain have temperatures lower and higher than the natural room temperature. Another research [11] on the example of wheat reported that the shearing energy increase with the grain size in two cases: when the load was applied to the grain in vertical and horizontal position. The same study also shows that the dependance between moisture content and shearing energy is nonlinear and the energy increase at first with the moisture content (MC) and for about 15% MC it begins to drop with MC increase. The similar observation of energy changes with moisture content was reported in [12,13]. In contrary Lupu et al. [14] found that the energy values for comminution decreases with the MC.

There are several studies concerns the relation between particle sizes and energy for biomaterials. Most available reports include the energy-size relationships for brittle materials such as rocks, stones, minerals. For those it was found that the breakage energy decrease with particle size and this dependance could be described by the negative power formula [15–17]. For biomaterials some studies shows that the energy decrease with particle height increase [1,2,18] or decrease in grain mass [19]. The changes of energy with the grains properties have an impact on the grinding machines performance, especially energy consumption as well the throughput and size reduction ratio [20–23]

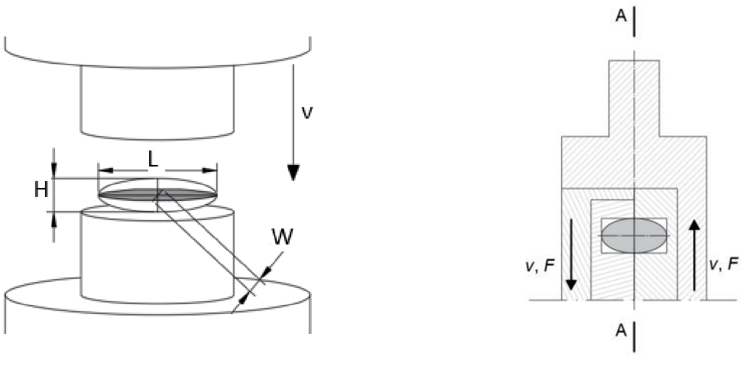
Taking into account the recent state-of-art the aim of this research is to expand the knowledge on the description of the biomaterials grains breakage energy. The experimental procedure is aimed to describe the relations between grains size and energy needed to cause the grain damage. Completion of the study allowed to find the answer for posted research question: how the grains size in the case of biomaterials grains influence the energy needed for breakage (damage) occurrence? In the experimental part grains was subjected to compression and cutting loads on an universal testing machine. Based on the force-displacement curves, the relationship between the energy necessary to cause a breakage and particle size was described.

2. Materials and methods

The size - energy relationship in this study was investigated on the example of rice (white rice) and corn grains. These grains are characterized by a different internal structure and thus characterized by different mechanical properties - rice is more brittle than corn. The main component of raw rice is endosperm (70%) followed by husk, bran and germ [24]. White rice arises as a result of husk, germ and bran removal [24]. Corn is composed of endosperm (containing mainly starch and proteins) and fibrous outer layer [25]. Both, corn and rice are widely used in food and feed industry and processed by harvesting, transporting, drying, comminution, etc, in which the breakage occurs [26–28]

The grains selected were cleaned before tests. To analyze the influence of grain size on the energy of breakage, two different test on the single grains were conducted, it is compression and cutting. The single grain loading tests are one of the widely used for describing energy of breakage [6]. Research involved 100 grains in each experiment. Prior the tests the size: height (H), length (L) and width (W) and weight (m) of each grain was measured. The size was taken with use of electronic vernier caliper and weight with use of laboratory scale. The moisture content was determined according to the ASAE S352.2 APR1988(R2017) standard [29] and calculated as a percentage share of mass loss during drying. The MC of grains subjected to cutting was 12.68 ± 0.01%, and 13.02% ± 0.01% for corn and rice, respectively. In compression, the grains of two levels of moisture content were used: 14% and 20%. To achieve different moisture content the grains were firstly moisturized to 28% MC and then dried in the room temperature.

Test were done with use of universal testing machines (Instron 5966 and MTS Criterion). The placement of grains in the machine during compression and cutting was presented on the Figure 1. The grains were compressed with the loading speed equal to 1.25 mm·min^{-1}, and cut with velocity v_s = 2 mm·s^{-1}. In each test the fore and displacement were recorded.



a) b)

Figure 1. Scheme of grain loading in single particle tests a) compression tests, b) cutting tests; H – height, W – width, L – length, v – loading rate, F - force

Based on the data from compression and cutting of single grain the force-displacement curves $F=f(D)$ were obtained. Then the energy values needed for cutting and compression were calculated as the area under the $F=f(D)$ curve according to equation [16,30]:

$$E_{(b,c)} = \int_{D_1}^{D_{(b,c)}} F dD \tag{1}$$

where: $E_{(b,c)}$ – energy needed for particle damage, subscripts b and c correspond breakage and cutting, respectively, J, F – force, N, dD – deformation to the point of particle damage, mm.
Then the mass specific energy was calculated based on equation [17]:

$$E_{m(b,c)} = \frac{1}{m} \int_{D_1}^{D_{(b,c)}} F dD = \frac{E_{(b,c)}}{m} \tag{2}$$

where m is the mass of a single grain expressed in kilograms.

3. Results and discussion

Figure 2 presents the results of calculated specific energy of rice and corn grains shearing in the compression test for different size ranges of grains.

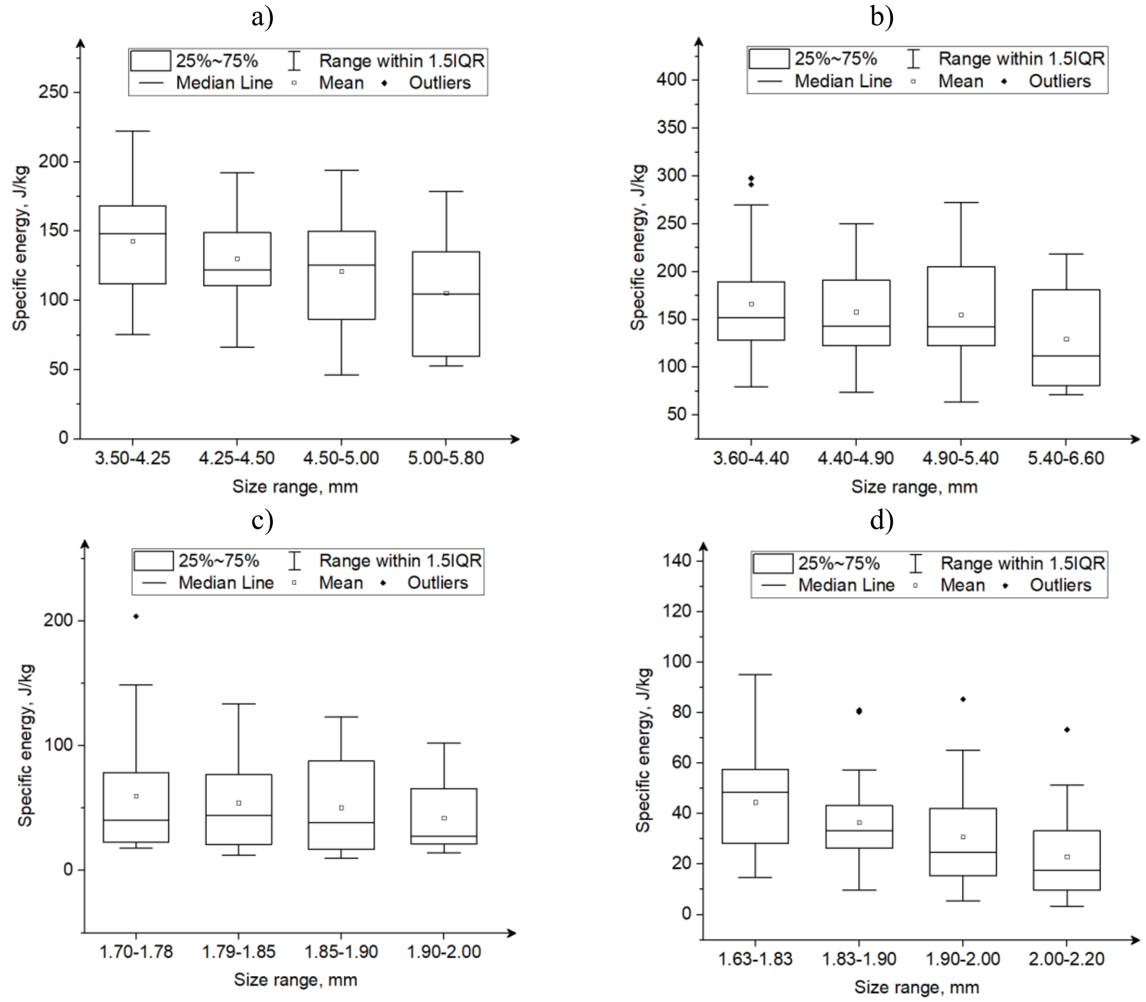


Figure 2. Energy of breakage for different particle sizes: a) corn 14% MC, b) corn 22% MC, c) rice 14% MC, d) rice 22% MC

The average specific energy of corn compression of 14% MC was lowest (105.411 J/kg) for particles with mean particle height of 5.5 mm and highest (142.85 J/kg) for particles with mean height of 4.01 mm. For corn of 22% MC the lowest energy (129.61 J/kg) was noted for the particles with mean height of 5.9 mm, and highest for particles with mean height of 4.16 mm. The lowest specific energy for rice (42.30 J/kg) with 14% MC was noted for grains with mean size of 1.95 mm and highest (59.85 J/kg) for mean height of 1.75 mm. For rice with 22% MC the highest and the lowest specific energy was 44.59 J/kg and 23.12 J/kg for particles with mean size of 1.76 mm and 2.05 mm, respectively. It was observed that the energy for compression decrease with increase in grains height of both, rice and corn and two MC. It can be seen, that for corn the energy needed to induce the breakage is higher for grains with 22% MC than for grains with 14% MC, while for rice the energy was higher for grains with 14% MC than 22% MC.

For specific energy in cutting tests the similar relation between energy and particles height is observed – the energy decreases with the increase in grains height (Figure 3). The average specific energy of corn cutting was lowest (176.61 J/kg) for particles with mean particle height of 5.48 mm and highest (212.93 J/kg) for particles with mean height of 4.32 mm. For rice with 22% MC the highest and the lowest specific energy was 328.02 J/kg and 247.82 J/kg for particles with mean size of 1.44 mm and 1.75 mm, respectively.

a) b)

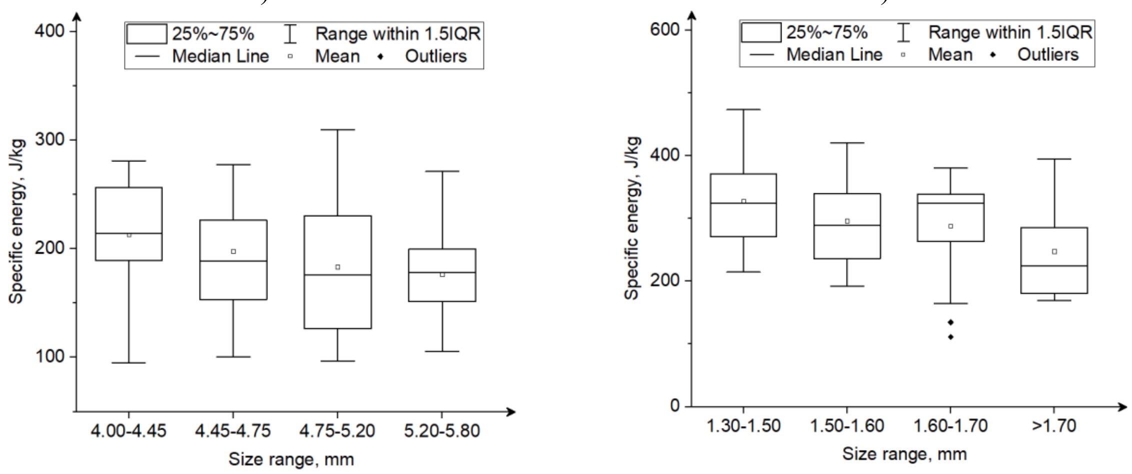


Figure 3. Cutting energy for different particle sizes: a) corn, b) rice

To describe the dependance between average specific energy and particle height the Pearson correlation analysis was done. The confidence level adopted was 0.05. The analysis shows that for performed compression and cutting tests the mean energy of grain shearing is strongly negatively correlated with the grain height (Table 1).

Table 1. The fitting functions of average specific energy needed for grain damage in dependence of grain size

		Compression		Cutting
		14% MC	22% MC	
Corn	r-Pearson's	-0.9921*	-0.95853*	-0.95915*
Rice	r-Pearson's	-0.99376*	-0.99842*	-0.98014*

2-tailed test of significance was used, (*) – correlation is significant at the 0.05 level

Based on the data about the mean energy needed to induce the breakage in the cutting and compression test, the dependencies describing the changes of energy with particles height were developed. Figure 4 shows the experimental data of mean energy for different corn and rice grains heights intervals together with the fitted curves.

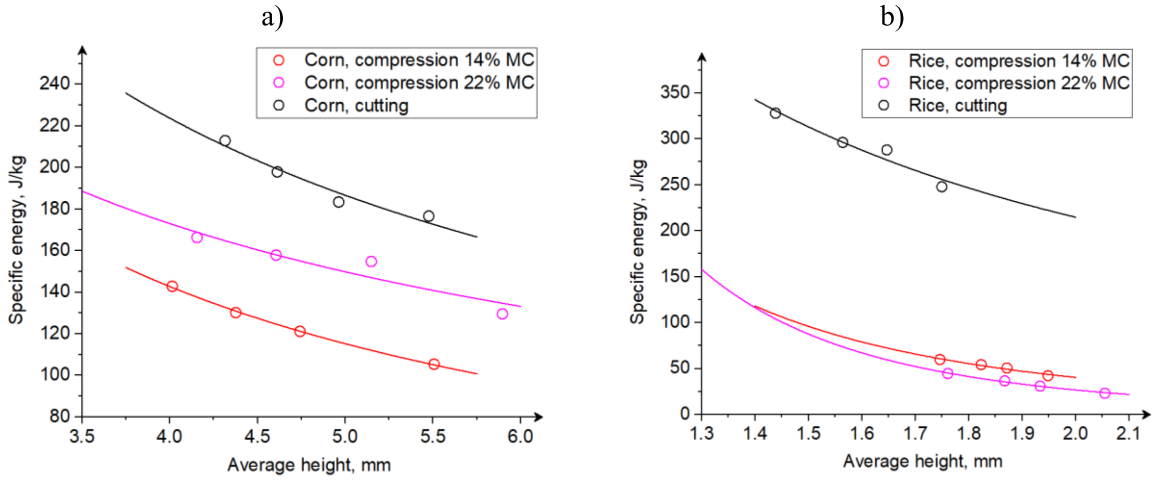


Figure 4. Cutting energy for different particle sizes: a) corn, b) rice. Solid lines are fitted power functions.

The relationship between particle size and rice and corn shearing energy during compression and cutting, as well both MC can be described with a high fit in terms of a decreasing power functions (Table 2), similarly as reported in studies for brittle materials [15]. The coefficients in the equations are function parameters, strictly dependent on the material properties. The study confirms the relations between grain size and breakage energy observed for brittle materials [16]. As was reported [31] larger particles are easier to crush, and thus the probability of grain damage is higher. Presumably, increasing the energy necessary to initiate a crack for small particles is related to the internal structure of the grain, the occurrence of microcracks [32].

Table 2. The fitting functions of average specific energy needed for grain damage in dependence of grain size

			Fitting function	R^2	Adj. R^2
rice	Compression	14% MC	$E_b(\bar{H}) = 325.29 \cdot \bar{H}^{-3.011}$	0.968	0.951
		22% MC	$E_b(\bar{H}) = 466.68 \cdot \bar{H}^{-4.126}$	0.990	0.985
	Cutting	13.02 MC	$E_c(\bar{H}) = 532.78 \cdot \bar{H}^{-1.311}$	0.941	0.912
corn	Compression	14% MC	$E_b(\bar{H}) = 539.75 \cdot \bar{H}^{-0.959}$	0.999	0.998
		22% MC	$E_b(\bar{H}) = 423.45 \cdot \bar{H}^{-0.645}$	0.877	0.815
	Cutting	12.68% MC	$E_c(\bar{H}) = 690.18 \cdot \bar{H}^{-0.813}$	0.951	0.926

4. Summary and conclusions

This study presents the relationship between the particle size and energy of grain shearing for biomaterials, such as rice and corn grains. The static compression test and cutting test were conducted to reveal the connections between particle height and energy for cutting and compression. It was found proved that the particle height affects the energy needed to cause grain damage.

This study leads to the following conclusions:

- the energy of breakage is lower for particles with bigger heights for both types of particle shearing mechanisms – compression and cutting,
- the dependencies between particle initial size is described by the power function,
- the energy of breakage is affected by the moisture content, for rice the energy was higher for grains with lower moisture content, for corn the energy was higher for grains with higher MC,
- the further research should be focused on development of the relationships between moisture content, particle size and breakage energy, as well probability of breakage.

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References

[1] Kruszelnicka W, Marczuk A, Kasner R, Bałdowska-Witos P, Piotrowska K, Flizikowski J and Tomporowski A 2020 Mechanical and Processing Properties of Rice Grains *Sustainability* **12** 552

[2] Kruszelnicka W 2021 Study of Selected Physical-Mechanical Properties of Corn Grains Important from the Point of View of Mechanical Processing Systems Designing *Materials* **14** 1467

[3] Bembenek M 2020 Exploring Efficiencies: Examining the Possibility of Decreasing the Size of the Briquettes Used as the Batch in the Electric Arc Furnace Dust Processing Line *Sustainability* **12** 6393

[4] Jewiarz M, Wróbel M, Mudryk K and Szufa S 2020 Impact of the Drying Temperature and Grinding Technique on Biomass Grindability *Energies* **13** 3392

[5] Chen Z, Wassgren C and Ambrose R P K 2021 Measured damage resistance of corn and wheat kernels to compression, friction, and repeated impacts *Powder Technol.* **380** 638–48

[6] Chen Z, Wassgren C and Ambrose K 2020 A Review of Grain Kernel Damage: Mechanisms, Modeling, and Testing Procedures *Trans. ASABE* **63** 455–75

[7] Otwinowski H 2006 Energy and population balances in comminution process modelling based on the informational entropy *Powder Technol.* **167** 33–44

[8] Otwinowski H, Zbroński D and Urbaniak D 2007 Experimental identification of entropy model of comminution process. *Granul. Matter* **9** 377–86

[9] Pandiselvam R, Thirupathi V and Mohan S 2015 Engineering properties of rice *Agric. Eng.* **XL** 69–78

[10] Romański L, Stopa R, Niemiec A and Wiercioch M 2006 Energy consumption of wheat grain during static shearing process *Inż. Rol.* **10** 153–9

[11] Romański L and Stopa R 2003 Energy consumption of wheat grain during shearing dynamic process *ACTA Tech. Agrar.* **2** 33–41

[12] Romański L and Niemiec A 2012 Badanie wpływu wilgotności ziarna wybranych gatunków zbóż na energię rozdrabniania w gniotowniku modelowym *Inż. Rol.* **9**(20) 255–251

[13] Romański L and Niemiec A 2001 Badanie wpływu wilgotności ziarna pszenicy na energię rozdrabniania w gniotowniku modelowym *Acta Agrophysica* **46** 153–8

[14] Lupu M I, Pădureanu V, Canja C M and Măzărel A 2016 The effect of moisture content on grinding process of wheat and maize single kernel *IOP Conf. Ser. Mater. Sci. Eng.* **145** 022024

[15] Gan D, Gao F, Zhang Y, Zhang J, Niu F and Gan Z 2019 Effects of the Shape and Size of Irregular Particles on Specific Breakage Energy under Drop Weight Impact *Shock Vib.* **2019** e2318571
[16] Tavares L M and de Almeida R F 2020 Breakage of green iron ore pellets *Powder Technol.* **366** 497–507
[17] Tavares L M, Cavalcanti P P, de Carvalho R M, da Silveira M W, Bianchi M and Otaviano M 2018 Fracture probability and fragment size distribution of fired Iron ore pellets by impact *Powder Technol.* **336** 546–54
[18] Dziki D and Laskowski J 2003 Influence of wheat kernel geometrical properties on the mechanical properties and grinding ability *Acta Agrophysica* **2** 735–42
[19] Wiercioch M, Niemiec A and Romański L 2008 The impact of wheat seeds size on energy consumption of thei grinding process *Inż. Rol.* **103** 367–72
[20] Tomporowski A 2012 Stream of efficiency of rice grains multi-disc grinding *Eksploat. Niezawodn. - Maint. Reliab.* **14**(2) 150-153
[21] Tomporowski A and Flizikowski J 2013 Motion characteristics of a multi-disc grinder of biomass grain *Przem. Chem.* **92** 498–503
[22] Kruszelnicka W, Hlosta J, Diviš J and Gierz Ł 2021 Study of the Relationships between Multi-Hole, Multi-Disc Mill Performance Parameters and Comminution Indicators *Sustainability* **13** 8260
[23] Mannheim V 2011 Empirical and scale-up modeling in stirred ball mills *Chem. Eng. Res. Des.* **89** 405–9
[24] Shafie N and Esa NM 2017 The Healing Components of Rice Bran *Functional Foods, Wonder of the World: Evidence-Based Functional Foods in Health & Disease* ed A Azlan, A Ismail, UPM Press, Selangor, Malaysia, pp 341–68
[25] Singh N, Kaur A and Shevkani K 2014 Maize: Grain Structure, Composition, Milling, and Starch Characteristics *Maize: Nutrition Dynamics and Novel Uses* ed D P Chaudhary, S Kumar and S Langyan, Springer India, New Delhi, pp 65–76
[26] Chandravarnan P, Agyei D and Ali A 2022 Green and sustainable technologies for the decontamination of fungi and mycotoxins in rice: A review *Trends Food Sci. Technol.* **124** 278–95
[27] Chhabra N and Kaur A 2017 Studies on physical and engineering characteristics of maize, pearl millet and soybean *J. Pharmacogn. Phytochem.* **6** 1–5
[28] Kibar H and Öztürk T Physical and mechanical properties of soybean *Int. Agrophys.* **22**(3) 239–244
[29] American Society of Agricultural and Biological Engineers 1988 ASAE S352.2 APR1988 (R2017) *Moisture Measurement - Unground Grain And Seeds*
[30] Sarker M S H, Hasan S M K, Ibrahim M N, Aziz N A and Punan Mohd S 2017 Mechanical property and quality aspects of rice dried in industrial dryers *J. Food Sci. Technol.* **54** 4129–34
[31] Taşdemir A 2009 Fractal evaluation of particle size distributions of chromites in different comminution environments *Miner. Eng.* **22** 156–67
[32] Tavares L and King R P 1998 Single-particle fracture under impact loading *Int. J. Miner. Process.* **54** 1–28