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Investigation effect of the process parameters in mechanical comminution on ceramic materials

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ABSTRACT

This paper presents the research results on the effect of crushing ceramic extinguishing chambers at different settings of the outlet slot size using a jaw crusher. The influence of the crusher outlet slot size on the crushing process parameters and the grain composition of the resulting product was analyzed, and the range of optimization of each parameter was determined. The problem of using ceramic material waste was solved. The research proved that the jaw crusher works well as a mechanical crushing method for obtaining a fraction of the product that can be used as a feedstock to produce ceramic materials. In this work, novelty crushing plates were used and crushing efficiency indices were obtained for different sizes of closed side setting outlet slots, which may be a contribution to future simulation studies.

Keywords: crushing efficiency, recycling of ceramic materials, extinguishing chambers, technical ceramics.

INTRODUCTION

The current technical development is conditioned by the development of modern materials [1–3], polymers and composites [4–6] or materials and coatings [7] which withstand longer operational period [8] and technologies [9–11], unfortunately it is also very energy-intensive [12]. European Union legislation requires that each product manufactured must have a developed processing and recycling technology, considering the principles of sustainability and environmental protection [13]. Therefore, it is essential to develop technologies to dispose of many products that still need to be recycled. One of the methods is research on the optimization of parameters of technological processes [14]. The article results from cooperation between the Faculty of Automotive and Construction Machinery Engineering of the Warsaw University of Technology and the Łukasiewicz Research Network - Institute of Ceramics and Building Materials, Ceramics and Concrete Department in Warsaw. Both units work and develop knowledge in the field of mineral materials and their impact on machines and the environment. Thanks to this cooperation, it was possible to determine the parameters of the process of recycling ceramic waste and its reuse in the production of technical ceramics.

Production and post-production waste is generated during the production of ceramic materials (structural, electro-technical, unique, and technical ceramics) [15]. While production waste [15] can often be easily reused in the production process, post-production waste [16], which, e.g., does not keep standards (dimensions, shape) or has been damaged in the process (e.g., during molding or firing), requires a unique process to be able to turn it back and reuse it in production as an additive to the raw material mix. The production process of ceramic materials can often be divided into three stages: the stage of molding compound preparation, the stage of molding compound shaping, and the stage of curing or firing. The second and third stages mainly cause large production waste. The molding compound shaping stage is commonly used by ceramic manufacturers because it allows for uniform compaction of the production mass in the mold. During the shape forming and mechanical processing of the raw molded pieces, up to 25% of the material, which is the production compound of uniform composition, falls off. Because of the form and density, manufacturers often do not reuse such waste in the production process. In the third stage, when the moldings are ready for firing and meet the required standards in terms of dimensions and shape, they are subjected to thermal treatment, which is a complicated process requiring handling and time. The firing process is extended in time and consists of a gradual increase in temperature (sometimes held to remove volatile compounds) until a maximum temperature is reached, which gives the final properties to the ceramic product. The firing temperature values are usually known, but the production technologist, by practical experience, examines and verifies production batches according to customer requirements, which often results in production losses in case of batch rejection due to failure to meet the criteria, e.g., standards for dimensions, cracks or physical parameters such as electrical conductivity, hardness, mechanical strength, porosity, and many others. Up to 10% of the finished product is rejected at this stage, which is difficult to recycle and is sent to special landfills for proper storage.

By carrying out a recycling process, such material could be reused in production. Therefore, the focus is on preparing such a process for the post-production waste of inserts for extinguishing chambers of SU high-current contactors. A jaw crusher will be used in the recycling process, producing aggregate with the highest possible content of fractions below 4 mm.

The first production stage, i.e., preparation of the production compound, involves proper preparation of raw materials such as Mulkorite, Kaolin, Palonka, etc. The raw materials should be prepared appropriately and with the specified quality, water content, and grain size. The issue of grain size is mainly essential in the process of manufacturing chamber inserts. Initially, the granules in the dry mixer are mixed in appropriate ratios. It is known from grain composition studies that for the chamber inserts produced at the Ceramics and Concrete Department in Warsaw at the Experimental Department of Special Ceramics, about 15% of the grain composition is material that can be replaced by processed post-production waste. Such waste, having its own physical properties as the finished product, must be suitably comminuted to the required grain size, described in the next part of the article.

In the second stage, the production waste can be reprocessed, for example, by grinding in mixers or mills, since the defective semi-finished product is unstable after shaping and is easily crushed. Ball mills [17] (with steel or alundum balls), high-speed centrifuges (rotary mills), or vibrating mills are used for this purpose. A technologist guided by experience defines the principle of use to achieve the appropriate material with specific physical properties. The material thus processed is returned to the first stage.

Jaw crushers are used in crushing nodes in rock mining processing plants as primary crushing machines [18, 19], sometimes also in the secondary crushing stage [20, 21]. There are two main types of jaw crushers, single toggle and double toggle crushers. They differ in the movement of the jaw. For rock processing, jaw crushers are recommended to crush feed with a degree of fineness of 3−4 [20]. Jaw crushers are also increasingly used to produce products from recycled materials, i.e., disassembled concrete material [22–32] and glass [13].

The economic and environmental benefits that can be obtained from waste minimization and recycling are significant [33, 34], as it benefits both the environment and companies in terms of cost reduction and the ability to sell or reuse certain waste materials [27, 33, 35–40].

Crushing of brittle materials is one of the most power-consuming [22, 41–46] and essential operations in aggregate production. A more comprehensive discussion of theories on the crushing processes of various materials [47–52], energy consumption [44], kinematics, and simulation of the crushing process [53] can be found in the literature [44, 54–67].

The process of crushing materials is energy-consuming. For more than a century, theories have been developed to establish the relationship between the crushing effect and the energy consumed in the crushing process. There is extensive literature on the so-called grinding hypotheses and their applicability in practice to describe real processes [68–73]. Guidelines for designing processing lines that crush different materials are still missing, so experimental studies are the best evaluation of these designs.

For the comminution of soft materials used in ceramics production, a high degree of fineness and usually three to four times crushing is used.

The paper is a study of the technological and economic aspects of using a jaw crusher in crushing ceramic material. It presents the research results on the example of a 4-stage processing system. It can be a tool for the analysis and study of the efficiency of aggregate production systems. Another problem concerns the adjustment of the outlet slot dimension, which increases during comminution and has to be adjusted manually or automatically to compensate for the wear of the jaw lining [53]. This work will provide information on how reducing the outlet slot affects the efficiency of the crushing process. The novelty of the work is the use of proprietary crushing plates and obtaining crushing efficiency indicators for different sizes of CSS (closed side setting) outlet slots, which may constitute an input for subsequent simulation tests.

AIM OF THE WORK

As already mentioned, the purpose of this publication is to carry out experimental verification of the effect of the CSS outlet slot dimension (Fig. 5a), including a new type of plate developed by the author on the efficiency of the four-stage process of crushing ceramic material, forces, energy, grain composition and to indicate the benefits of the implementation of crushing. The study's results allowed for the development of a model of the ceramics recycling process, taking into account the influence of the basic parameters of the crushing process on its efficiency. This made it possible to carry out calculations necessary to design and construct a crushing node in a ceramic production plant. The ceramic waste will ultimately be used as an ingredient in products for the ceramics industry.

TEST MATERIAL

Tests were carried out using ceramic material, which is used to manufacture arc and extinguishing chambers for SU contactors (Fig. 1a). The extinguishing chamber for the SU contactor is used to cool, divide, and expand the arc of the arc column.

In a contactor or circuit breaker, an electric arc is pushed by electromagnetic induction forces into an extinguishing chamber. The extinguishing chamber is usually built in the form of several conductive plates on which the arc column is divided into several sections. The SU contactor is used in high-current circuit breakers in DC and AC circuits to control motors with heavy starting and counter-current braking. Table 1 shows the basic dimensions of the contactors used. The completed extinguisher chambers pass quality control and are subjected to a final test for bending strength. The chambers during the test (destructive testing) are shown in Fig. 1b. These chambers must operate for 10000 on/off cycles under load. The bending strength of the chamber and the maximum load are determined during testing (Table 2). As shown in Table 2, the maximum load, like the bending strength, does not depend on the chamber size. Quality control standards of maximum load > 400 N are adopted in the plant.

(a)

(b)

Figure 1. Extinguishing chambers during: (a) production (after firing and before testing), (b) strength test

Table 1. Basic parameters of the tested contactors

Lp.	Contactor type	Mass per piece [g]	Length [mm]	Water absorption [%]
1.	SU 0/1	190 ± 10	161 ± 1.5	12 ± 1
2.	SU 2/3	365 ± 10	179 ± 1.5	12 ± 1
3.	SU 4	560 ± 20	200,0 ± 2.0	12 ± 1
4.	SU 5	790 ± 30	239,0 ± 2.5	12 ± 1
5.	SU 6	1080 ± 30	246 ± 2.5	12 ± 1

Table 2. Characteristics of the studied inserts material

Contactor type	Max load [N]	Bending strength [MPa]	Thickness [mm]	Width [mm]
SU − 2/3	455	13.00	7	15
SU − 4	506.7	6.26	10	17
SU − 4	445.3	5.50	10	17
SU − 4	465	5.74	10	17
SU − 4	544	6.72	10	17
SU − 5	410	4.99	12	20
n	6	6	6	6
Average	471	7.03	9.83	17.17

TEST EQUIPMENT

A laboratory Blake-type jaw crusher was used in the study. The stand is equipped with specialized recording and control equipment [74]. The measuring apparatus for testing the crusher consists of the front toggle plate after appropriate structural changes: sticking strain gauges and calibration, which at the same time serves as a force transducer in the toggle plate and a strain gauge transducer to measure the displacement of the moving jaw. The basic parameters of the jaw crusher are as follows: inlet slot dimensions − 100×200 mm, outlet slot adjustment range − 18 mm, electric motor power − N_s = 4 kW.

During the tests, changes in the force in the front toggle plate and the displacement of the moving jaw as a function of time were recorded. The force does work on the path corresponding to the energy accumulated in the crushing of the raw material and some kinematic members of the lever mechanism. The energy loop is the basis for determining the crushing energy [74]. Example diagrams of force in the toggle plate as a function of moving jaw displacement are shown in Figure 2 for five consecutive crushing cycles.

The crushing process is cyclic. It can be observed that as the moving jaw approaches the fixed one, the force increases unevenly. The highest values of the compressive force are found around the point of maximum jaw approach (CSS). It can be seen that the stroke of the moving jaw decreases as the load increases, which is related to the susceptibility of the crusher. During the return movement, the elastic energy accumulated in the material and the crusher components is recovered

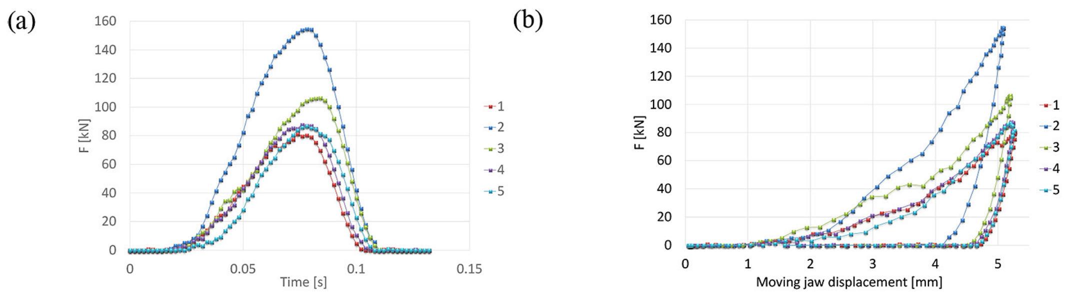

Figure 2. Five consecutive crushing cycles of the material in the first crushing stage I: (a) force vs. time diagram, (b) crushing force as a function of displacement of the crushing jaw

and supplied to the flywheels through the toggle plates. As the stroke decreases, the maximum crushing force required to crush the feed increases, and the machine performance is in simple relation to the jaw stroke. In the case shown in Figure 2, the maximum reduction in stroke is about 5. To compare the effects of fragmentation for individual outlet slots, a group of indicators for forces, energy, efficiency, and degree of fineness was introduced (Table. 3). The method of their determination is presented in [75, 76].

Figure 3 shows an exemplary plot of changes in forces in the toggle plate for the outlet slot CSS = 5 mm and 3.1 mm for the first crushing stage. The tests were recorded with a time step of 2 ms. It was observed that depending on the tested dimension of the outlet gap, there is a different duration of the crushing process, which is related to the crushing efficiency and energy (Table. 3). It was also observed that the value of the average force is related to the size of the outlet slot. To determine it, Equation 1 was used:

$$\bar{F}_{av_{max}} = \frac{1}{k}\sum_{i=1}^{k} F_{maxi} \tag{1}$$

where: F_{maxi} are maximum values in subsequent cycles of operation, k – number of subsequent cycles of operation.

Table 3. The values of examined indicators in the first series of crushing

Parameters, indicators	I	II	III	IV
Outlet slot CSS [mm]	5			
Technical performance [Mg/h]	0.65	0.82	0.87	0.97
Performance of 0−4 mm class [Mg/h]	0.30	0.45	0.40	0.35
Effective energy [kWh]	0.00469	0.00171	0.00056	0.00016
Specific energy [kWh/Mg]	1.07	0.69	0.51	0.25
Maximum crushing force [kN]	155.27	130.62	112.36	50.25
Crushing time [s]	21.11	8.95	3.84	2.08
Specific crushing time [h/Mg]	1.54	1.22	1.15	1.03
Feed grain size D_{80} [mm]	100.00	10.03	7.30	7.06
Product grain size d_{80} [mm]	7.41	6.55	6.76	6.90
Degree of fineness i_{80} [-]	13.50	1.53	1.08	1.02
Outlet slot CSS [mm]	4			
Technical performance [Mg/h]	0.47	0.65	0.70	0.81
Performance of 0–4 mm class [Mg/h]	0.27	0.43	0.35	0.24
Effective energy [kWh]	0.00543	0.00163	0.00029	0.00007
Specific energy [kWh/Mg]	1.32	0.87	0.51	0.23
Maximum crushing force [kN]	161.98	147.94	89.11	42.76
Crushing time [s]	25.65	7.57	2.46	1.06
Specific crushing time [h/Mg]	2.14	1.53	1.43	1.23
Feed grain size D_{80} [mm]	100	6.92	6.87	6.66
Product grain size d_{80} [mm]	6.51	5.83	6.51	6.92
Degree of fineness i_{80} [-]	15.37	1.19	1.06	0.96
Outlet slot CSS [mm]	3.1			
Technical performance [Mg/h]	0.44	0.48	0.68	0.65
Performance of 0−4 mm class [Mg/h]	0.24	0.36	0.30	0.19
Effective Energy [kWh]	0.00507	0.00133	0.00036	0.00009
Specific energy [kWh/Mg]	1.24	0.92	0.48	0.26
Maximum crushing force [kN]	154.03	106.43	69.13	37.14
Crushing time [s]	24.29	7.56	2.92	1.64
Specific crushing time [h/Mg]	2.27	2.08	1.48	1.53
Feed grain size D_{80} [mm]	100.00	7.80	7.53	7.25
Product grain size d_{80} [mm]	6.62	4.87	6.60	6.87
Degree of fineness i_{80} [-]	15.11	1.60	1.14	1.06

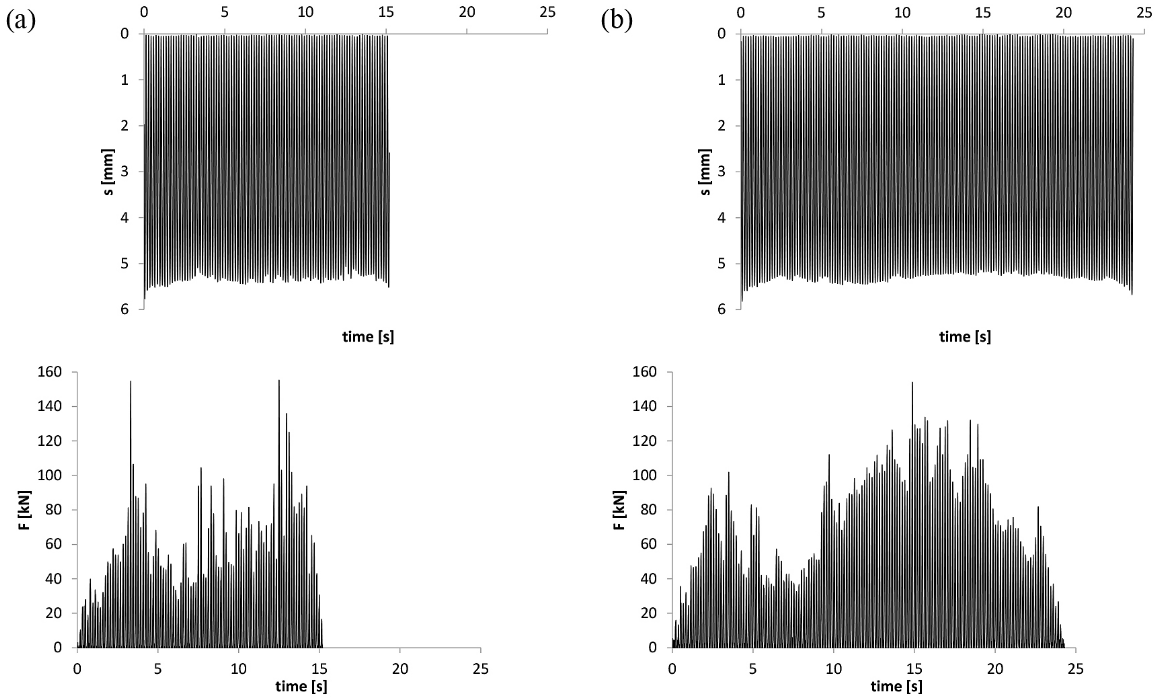

Figure 3. Jaw throw and force history in the toggle plate for laboratory crusher – I[st] crushing: (a) outlet slot CSS = 5 mm, (b) CSS = 3.1 mm

As it was noticed after calculations, the reduction of the outlet slot dimension by 38% (from CRR = 5 mm to CSS = 3.1 mm) resulted in a slight increase in the average crushing force value of about 18.5% (from 61.94 kN to 76.05 kN).

Figure 4 shows the jaw throw values at which the force per cycle reached its maximum for two exemplary measurements.

RESEARCH PROGRAM, EXECUTION AND RESULTS

The research program included the determination of the influence of the outlet slot dimension on the following parameters of the crushing process: grain size of crushing products, crusher performance, performance of 0–4 mm grain

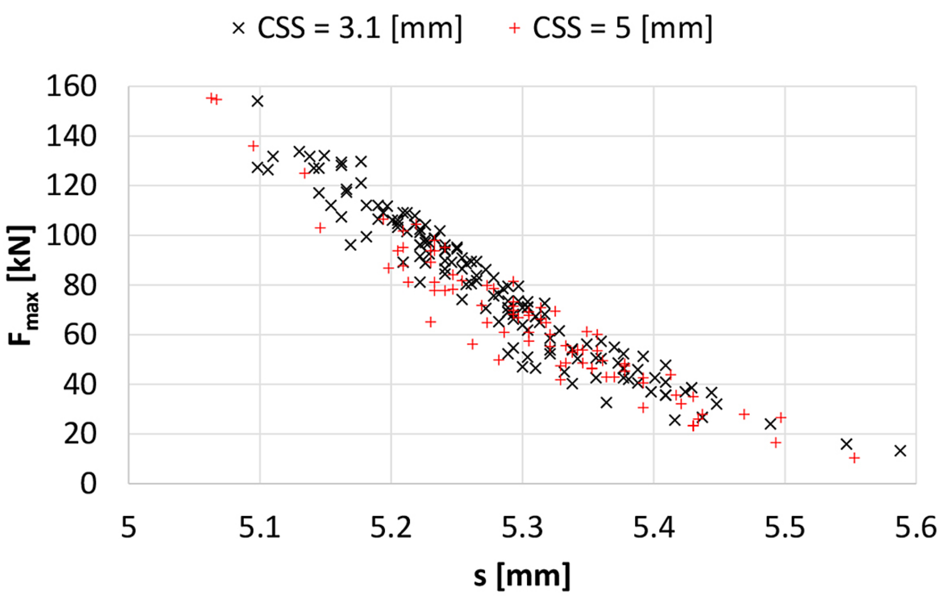

Figure 4. Jaw throw size for maximum crushing forces F_{max} in a cycle, I[st] crushing stage

classes, crushing energy, crushing forces, and degree of fineness.

Three outlet slot values were adopted in the crusher tests: CSS = 3.1 mm, CSS = 4 mm, and CSS = 5 mm. The outlet slot measurement method is shown in Fig. 5a. Tests were performed on innovative crushing plates with variable pitch (Fig. 5b, c) [75,76]. The tests use plates made of 45 steel, whose hardness on the HRC scale is 43–44.

The next research stage was to verify the usage of the product after the crushing process as a material added to the production compound as a substitute for a specific base substance. The described actions aimed to analyze the possibility of implementing a new way of recycling the mentioned material, which would reduce its depositing in the environment.

Crushers or mills mechanically crush brittle (high hardness) materials depending on the required fraction and feed size. Often, a hybrid model based on combining crushers and mills as cooperating equipment is used in the crushing process to determine the small grain size of the product.

In laboratory tests, the answer to the question of what the set outlet gap of the crusher should be to obtain as much product as possible with a grain size smaller than 4 mm was looked for.

Figure 6 shows example photos of the samples used in research. The feed prepared for testing consisted mainly of non-cubic grains.

Thus, prepared waste was subjected to a crushing process in a jaw crusher. After crushing, the material was subjected to sieve analysis and then sorted into two fractions: fine grain size 0–4 mm and coarse grain size above 4 mm. Grains with a diameter greater than 4 mm were again fed into the crusher, as shown in Figure 7. Material with grains more significant than 4 mm was crushed four times.

The crushing efficiency was evaluated using the sieve method; the crushed material was sieved through a set of sieves (Fig. 7) according to [77]. Based on the results of the share of each grain class, a summary granulometric distribution of the ceramic samples was obtained depending on the different sizes of the CSS

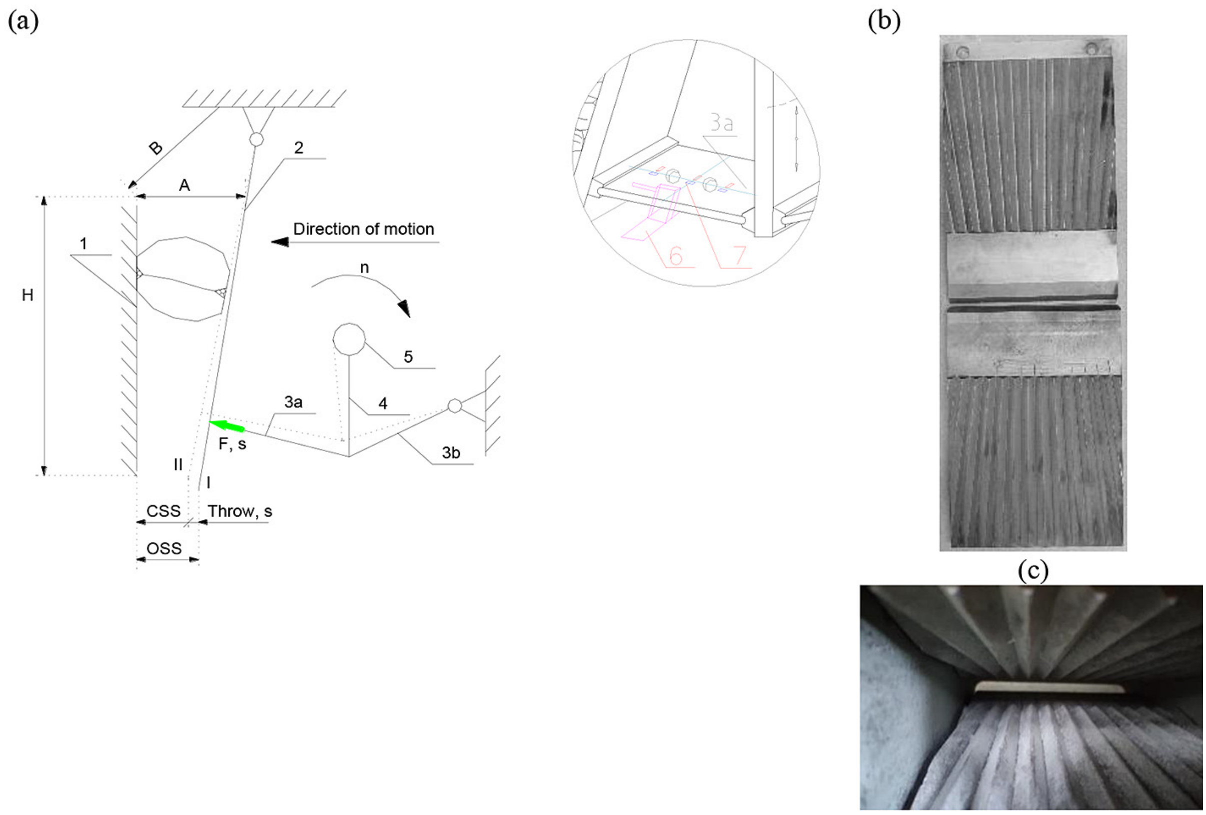

Figure 5. Laboratory jaw crusher: (a) measurement of the outlet slot: I − jaw crusher in open side discharge setting − OSS, II − jaw crusher in closed side discharge setting − CSS, (b) crushing plate profile, (c) top view of the crushing chamber, 1 – fixed jaw, 2 – moving jaw, 3a, b − front end rear toggle, 4 − pitman, 5 − eccentric shaft, 6 − moving jaw displacement system, 7 – F – force measurement system, A × B = 100 × 200 mm, H = 250 mm

Figure 6. Waste ceramic materials: (a) in feed form, (b) in crusher feed hopper, (c), (d) after crushing

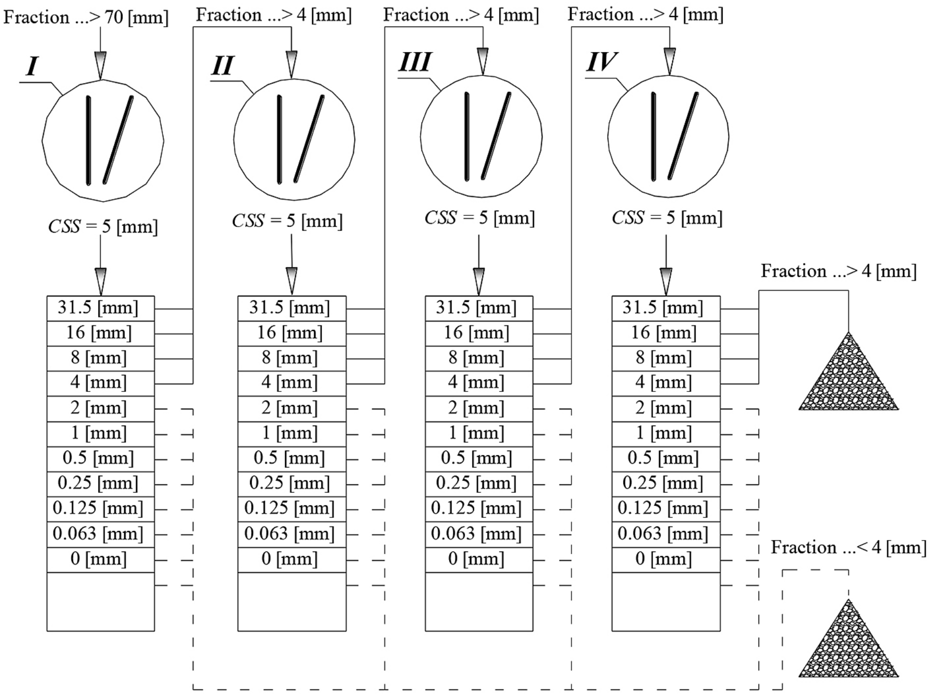

Figure 7. Example of crushing scheme for CSS = 5 mm

outlet slots (Fig. 8). The grain distribution curves obtained for the II[nd] crushing stage show that decreasing the outlet slot had a positive effect on increasing the desired grain class at the expense of a higher fraction.

EVALUATING THE EFFICIENCY OF THE MODEL PROCESS

Predicting the crushing effect is the basis of process line system design, crusher selection, and process efficiency. The parameters used to measure the impact of the crushing process are process efficiency, grain composition of crushed product, crushing forces, and crushing energy [41, 78, 79]. This study was interested in the relationship between crushing energy, forces, efficiency, and CSS outlet slot value. Research on the efficiency of crushing processes with plates of different shapes was carried out on a prototype laboratory crusher, the description and results of which have been presented previously [75, 76, 80]; the results presented in the mentioned works justify the desirability of conducting further model and experimental studies of machine crushing processes.

Several factors influence the efficiency of machine processes in the crushing machines' working space. These include the dimensions of the crushed feed, the hardness of the material, the shape of the crushing plate surface, and the shape of the chambers. Handbooks and papers devoted to mineral processing generally discuss the concept of process efficiency in the context of technology [81, 82]. It means qualitative and quantitative results of the processes usually understood

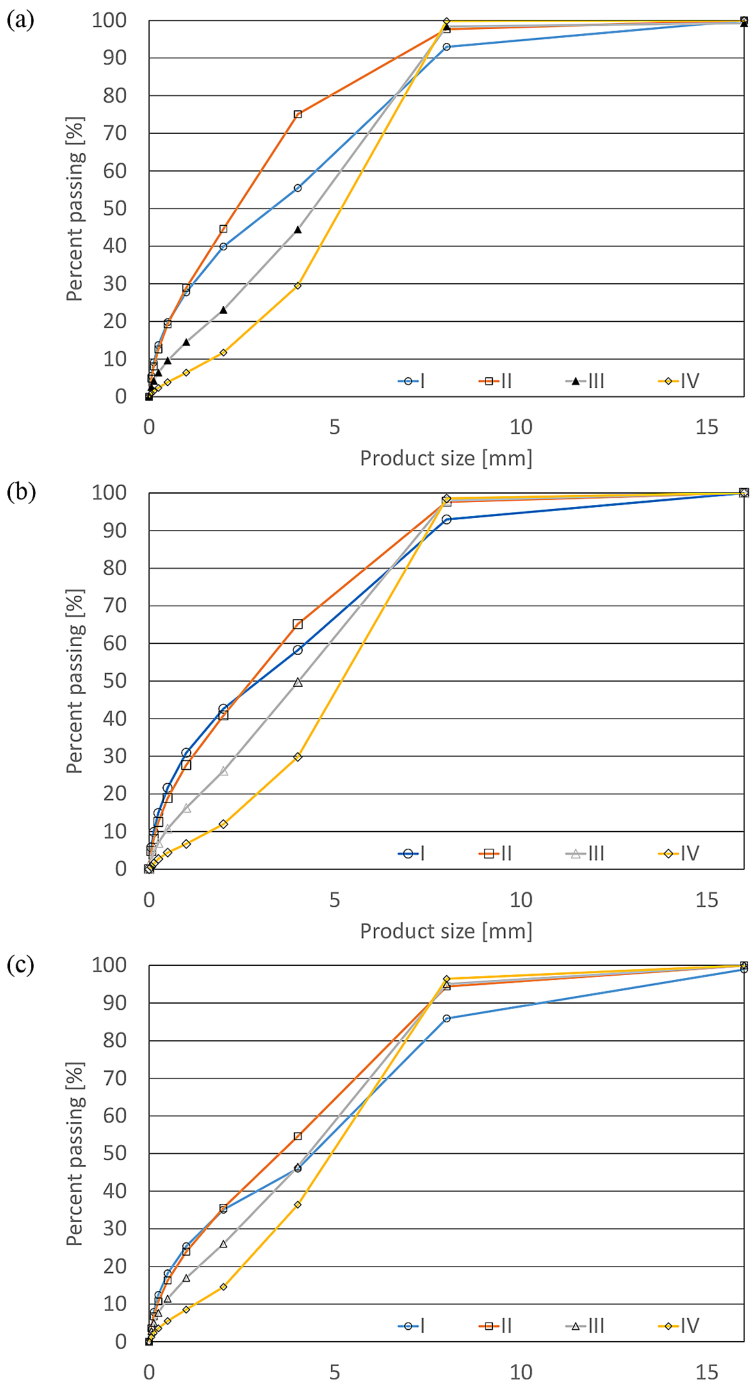

Figure 8. Grain composition curves of products obtained after four crushings of feed grains coarser than 4 mm for: (a) CSS = 3.1 mm, (b) CSS = 4 mm, (c) CSS = 5 mm

as, e.g., the degree of fineness, technical or operational efficiency, grain composition of the product described by the grain size distribution curves, the content of regular and irregular grains in the product, etc.

In the context of crushing mechanics, the following postulates are studied: firstly, minimum forces - the process should be carried out with the lowest possible limit forces, which influences the design of machine components. Secondly, the postulate of minimum energy [73, 83] − knowledge of the energy consumed in the process is of great importance in the rational selection of the drive system. Thirdly, the postulate of obtaining a significant reduction of body dimensions, which is related to the size of newly created surfaces.

To compare the effects of the different settings of the CSS crusher outlet slot, a group of indicators was introduced, the values of which are shown in Table 3, and their determination method was presented previously [74–76].

The first indicator considered is the unit crushing energy L_s as a ratio of the energy L_e consumed in the process to the mass m of the product obtained:

$$L_s = \frac{L_e}{m} \quad (2)$$

Determining the amount of energy required to crush a given material is extremely important in designing a technological system and, in particular, selecting equipment in terms of both type and size. The second indicator is the maximum crushing force defined by Equation 1. Another quantity that determines efficiency should be the area increment ΔA.

Since it is difficult to determine it in machine processes, it is more convenient to introduce other quantities indirectly related to the area gain. These quantities are the degree of fineness and the performance. The apparent, boundary, 80%, and average degree of fineness are defined depending on how the grain size of the feed and product is determined. The degree of fineness is defined as the ratio of the average dimensions of the material before crushing to its average dimensions after comminution [84–86]. A popular form of the degree of fineness is the so-called i_{80}:

$$i_{80} = \frac{D_{80}}{d_{80}} \quad (3)$$

where: D_{80} – is the dimension of the screen opening through which 80% of the feed material passes, and d_{80} – is the dimension of the screen opening through which 80% of the comminution product passes.

In aggregate production, the grain size of the product is of significant importance; designers in various industries are trying to develop new high-efficiency crushing machines and methods to obtain the appropriate grain size of the product according to the demand [87, 88].

The performance W is the ratio of the mass of product m obtained in a process to the time duration t_p of that process. The expression for the performance W can be written as follows:

$$W = \frac{m}{t_p} \quad (4)$$

The crushing efficiency of ceramics is strongly influenced by features such as grain composition, shape of the feed grains, and water content. Since the shape of the feed of the analyzed ceramics is irregular, it is necessary to explain how the authors determined its average dimension because it affects the obtained result of the degree of fineness. The classification method is most commonly used in the literature for grain shape analysis. It is assumed that if the dimensions of grains b/a >2/3 and c/b >2/3, then such grains are considered cubic (a − length, b − width, c − thickness). Caliper measured the grains on the first crushing stage, and the size (diameter) of the feed grains was taken as its width as recommended in [82]. At subsequent crushing stages, the diameter was read from the sieve analysis. Jaw crushers are evaluated according to the maximum dimensions of their inlet slot, defined by the gap and width of the plates. It is common practice to limit the largest rock particle entering the jaw to no more than 80% of the inlet slot dimension [89]. As can be concluded by analyzing the performance calculation models (Rose and English Method, Taggart Method, Broman Method, Michaelson's Method) presented in [57], most of these calculation methods indicate higher performance than those reported by crusher manufacturers.

To indicate which process is more efficient, two crushing processes (process I and process II) run in the same machine but differ in the setting of the outlet slot are compared.

If there is a relationship between processes I and II:

$$\begin{gathered} L_{sI} < L_{sII} \\ F_{avmaxI} < F_{avmaxII} \\ i_{80I} > i_{80II} \\ W_I > W_{II} \end{gathered} \quad (5)$$

then process I is more efficient than process II. When there are other relations between them, it cannot be stated which of these processes is more effective. To resolve this, it is necessary to introduce the concepts of partial efficiency indicators and the concept of an indicator that comprehensively characterizes the process.

The energy efficiency index k_L is equal to:

$$k_L = \frac{1}{L_s} \quad (6)$$

while the force efficiency index k_F will be written as:

$$k_F = \frac{1}{F_{avmax}} \quad (7)$$

The efficiency index of the degree of fineness k_i and performance is determined as:

$$k_i = i_{80}$$
$$k_W = W \tag{8}$$

The k_e efficiency index characterizing the whole process is equal:

$$k_e = k_L \times k_F \times k_i \times k_W \tag{9}$$

Analyzing the equations above, it can be seen that the efficiency indicator depends directly on the degree of fineness and efficiency and is inversely proportional to the crushing energy and forces. In the evaluation of efficiency, it is assumed that the desired state is the one in which $W \rightarrow \infty$, $i_{80} \rightarrow \infty$, $F_{avmax} \rightarrow 0$. and $L_s \rightarrow 0$, so the better process will be the one which has a higher value of k_e index.

Table 3 shows the average values of the basic parameters of the crushing process for the three analyzed values of the outlet slot size. Seven measurements were made for each crushing stage (I-IV). The crushed material is technical/industrial ceramics. Crushing in a jaw crusher is intended to prepare fractions for grinding in order to obtain the appropriate grain size, therefore it is important to obtain as many fractions as possible below 4 mm.

DISCUSSION OF THE RESULTS

Table 4 shows the amount of the 0−4 mm fraction obtained depending on the size of the CSS outlet slot and the number of passages. The results show that decreasing the size of the outlet slot increases the proportion of grain classes 0−4 mm at the expense of higher grain classes, which is beneficial for the analyzed process.

There is a close relationship between the size of the crusher outlet slot and the processes occurring in the machine. As can be seen, the second crushing stage (II) resulted in about 75% of the crushed grains, which were material with grain size below 4 mm. The next two crushings (III and IV) of grains above 4 mm (Table 4 part a) are no longer as effective.

With the assumed crushing parameters (Table 4 part b − stage IV), about 92% of the class with grain size 0−4 mm can be obtained

Table 4. Share of grains below 4 mm in the production of fragmentation depending on the amount of fragmentation of grains above 4 mm

Crushing stage	a) Percentage of grain grade in successive crushings [%] for			b) Percentage of grain grade in total [%] for		
	CSS = 5 [mm]	CSS = 4 [mm]	CSS = 3.1 [mm]	CSS = 5 [mm]	CSS = 4 [mm]	CSS = 3.1 [mm]
I	46.02	58.23	55.45	46.02	58.23	55.45
II	54.60	74.47	75.07	75.54	85.52	90.53
III	46.54	49.74	44.43	86.95	92.74	92.63
IV	36.41	29.83	29.48	90.73	94.95	95.71

Table 5. Dependence of the obtained average degrees of fineness i_{80} on the number of crushing stages (I, II, III, IV)

No.	CSS = 5 [mm]	CSS = 4 [mm]	CSS = 3.1 [mm]
I	22.83	22.59	26.60
II	22.32	21.41	25.21
III	20.67	20.30	23.58
IV	13.50	15.37	15.11

Table 6. Crushing efficiency index k_e for different outlet slots

No.	CSS = 5 [mm]	CSS = 4 [mm]	CSS = 3.1 [mm]
Crushing stage		k_e [kWh×1/kN×1/h]	
I	0.0788	0.0791	0.0714
II	0.0164	0.0163	0.0234
III	0.0139	0.0060	0.0078
IV	0.0528	0.0338	0.0348

in relation to the whole feed flow rate (for four crushing stages).

Table 5 contains the obtained values of the degree of fineness i_{80} as a function of the number of crushing stages for the three outlet slot sizes. The degree of fineness of the entire process (system) can be written with the equation:

$$i_{80} = i_{80I} \times i_{80II} \times i_{80III} \times i_{80IV} \quad (10)$$

where: i_{80n} fineness steps n = I, II,..., consecutive crushing stages.

In Table 6, the calculated values of the efficiency index are given. Conducted tests showed that crushing is most effective for the IV[th] crushing stage, but the least desirable 0–4 mm fraction is obtained.

CONCLUSIONS

As can be seen from the considerations made in this paper, when determining the parameters of the crushing process, several different factors, often canceling each other out, must be taken into account. Therefore, when selecting the appropriate dimension of the CSS outlet slot, a compromise must be reached to ensure optimal parameters of the machine process and maximum crushing of rock material at the lowest possible power consumption and crushing force. On this basis, it can be clearly stated that determining the dimension of the outlet slot in the jaw crusher in terms of the maximum degree of fineness and, thus, optimal load on the plates requires finding an appropriate compromise between the parameters relevant to this issue. It is impossible to select appropriate values for the crusher's design parameters by analyzing them selectively or without considering their mutual influence on each other.

The crushing efficiency index for different sizes of CSS outlet slots combines their efficiency, unit work, crushing forces, and degree of fineness obtained. Different crusher outlet slots can be conveniently compared with each other based on their value. Reducing the CSS outlet slot reduces the efficiency of the process, increases the crushing energy, and decreases the crushing forces.

The conducted research confirmed the effectiveness of crushing ceramics with a laboratory crusher, which could also be used for commercial applications in enterprises with small processing needs. Determining the efficiency of the crushing device is also important from the point of view of selecting devices cooperating with production [90, 91], such as feeders or transport conveyors [92–95]. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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