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CORRELATION OF ENERGY CONSUMPTION AND SHAPE OF CRUSHING PLATES

1. Introduction

Mineral raw materials disintegration, in general, is a high energy consuming process. The available literature data [1] present shows that rock comminution operations in the USA cover 30% of the total costs of energy consumed in the mining industry. It accounts for 0.4% of energy consumed in the country. In Australia the amount of energy used for the industrial comminution processes approaches up to 1.5%, while in Canada and South Africa that index comes to 2%. It may be estimated that industrial comminution consumes more than 3% of the global production of electric energy in the world [2].

Technological projects should consider the constrains on the costs of industrial comminution processes. The problem brings some of the difficulties home because theoretical analysis is highly confined and in practical terms the experiments and monitoring of the machine processes ore established as the only information source. One of the ways to cut the comminution process cost is to reduce forces and energy consumption in maintaining machine output by the proper design of working elements such as crushing plates.

As it is known, the shape of the crushing plates of a jaw crusher (even the crushing space in roll crushers) and the crushing processes are strictly related. The effects of this can be only established experimentally. The literature of the subject [3–5] covers a few papers concerning some technological aspects. It should be noted that problems surrounding crushing plate design is neglected by scientists and engineers. Attention is mainly devoted to crushing space development. In fact, the working surface and shape of the crushing plates remains unchanged since compression type crushers were industrially implemented [6]. Three different patterns of cross section profiles of the crushing plates: smooth, triangle and trapezoid which are most frequently used. Applicability of the mentioned profiles is related to the material being

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processed (smooth plates or tough rocks: basalt, granite, metal ores etc.). Similarly the traditional guidelines specify the dimensions of geometric profiles, such as angle wedges, pitch and width of the trapezoid profile vertices. The specific feature of these profiles is that the whole surface of the plate is invariant and is not adapted to the strength characteristics of rocks.

The article presented shows the results of tests on new plate designs with respect to the crushing energy consumption. These are plates of a variable profile. The idea of such a concept results from simple observations — the best profile should be adapted to the size of the crushed lumps, and therefore should be variable. In addition, this profile should be adapted to the material strength characteristics.

The proposition of using variable profiles of crushing plates was brought in by J. Zawada in the 1980`is and 1990`is [7, 8]. In the paper presented demonstrated that the use of variable transverse profile can significantly reduce the load limit (approx. 30% compared to traditional plates used for marble disintegration) [9].

2. The objective of the work

Force research previously conducted [10] for eight sets of crushing plates demonstrated that the smallest crushing forces appeared during the process of grinding between plates of a variable height and pitch.

The experiment was conducted within the framework of the paper was to investigate the relationship between the properties of various, materials (limestone, sandstone, granite) and the shape of crushing plates under the constant technical-operational parameters of the crushers. The results of the experiment were to give an answer to the question to what extent the individual characteristics of the raw materials and the setting and pitch and the size of the crushing notches affect the energy consumption process.

The second part of the work concerns the calculation of the energy consumption. The method applied is based on the Bond hypothesis. Existing surveys show that crushing energy calculated by means of this hypothesis is the closest to reality. An alternative calculation method was proposed. As the grain size distribution of the final product is accounted for it shows a more accurate predictions of the experimental data.

3. Description of the experiments

In order to optimize the shape of the crushing plate, with respect to the forces and energy consumption of the process, tests of specific settings of the plates in the jaw crusher working chamber were been carried out. The smooth and profiled plates as well as the settings of the two different profiled plates were considered. These consisted of a plate with a smooth surface together with triangular surface plate (Fig. 1f), plate with a smooth surface and variable profile plate (Fig. 1g) and triangular and variable profile plate (Fig. 1h). In the experiments, the settings of the same type of plates were tested: smooth plates (Fig. 1a), triangular profile (Fig. 1b, c) variable-pitch and height of the profile (Fig. 1 d, e). The mentioned profiles and the plate settings are shown in Figure 1.

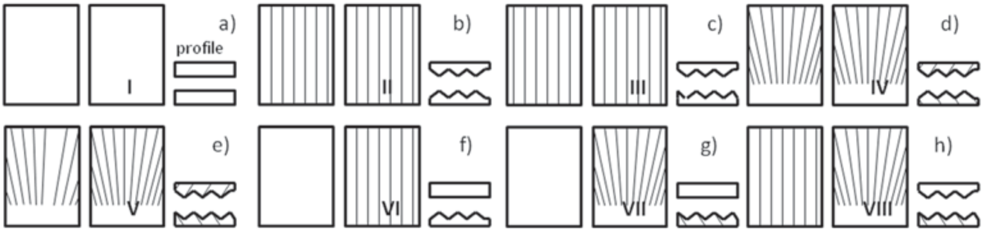


Fig. 1. Crushing plates used in the laboratory tests: a) smooth, b, c) triangle notches d, e) variable pitch and height of jaw tips, f, g) combined systems of plates

In order to compare the results, the crushing tests were conducted for constant value of the output slot, e_r = 24 mm. The principle of measurement of the output slot is shown in Figure 2.

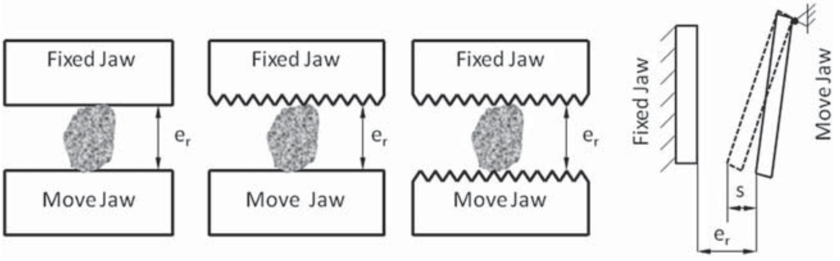


Fig. 2. The schema of the measurement of output slot size e_r for different jaw systems, s-jaw stroke

Three types of Polish rocks were used in the test, namely compact limestone of the Kielce region (Morawica limestone), sandstone of the Śleszowice region (Mucharz sandstone), and granite of the Strzegom. 120 samples were prepared for the experiments from a set of lumps of various sizes and shape. Each sample contained of 5–10 lumps depending on the material. The samples were characterized by an average dimension Dśr treated, as the arithmetic mean of the geometric dimensions of the individual lumps. The mass of the samples were settled in the range 3.4–3.98 kg [10].

The laboratory test used a double-toggle jaw crusher to perform the experiment. The machine, with different scale characteristics, fully corresponds to the structural and functional features of industrial jaw crushers. The parameters of the crusher (Fig. 3) are as follows: the dimensions of the input slot a×b = 100×200 mm, height of the crushing chamber h = 250 mm, jaw stroke s = 2–6 mm. An electric motor (type SZJe 34b) of power rated N_{zn} = 4 kW and transmission belt gear, i = 3.2, was implemented to drive the Crusher. Shaft crushers at idling speed are equal to n = 388 rpm.

4. Crushing energy

In the results of measurements of the force against the jaw displacement (Fig. 3) a graph presented in Figure 4 was used. On this graph it is possible to distinguish the two stages of

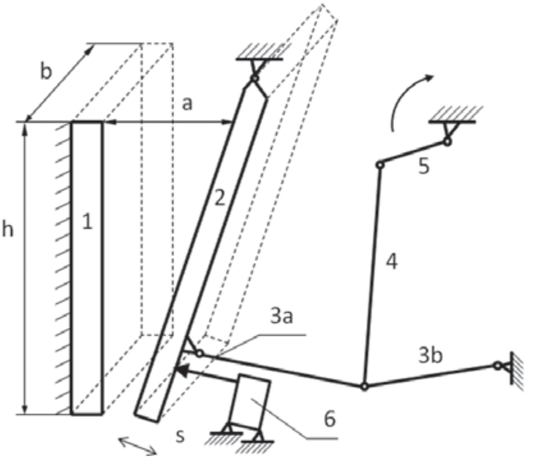


Fig. 3. Gauges localization scheme: 1-toggle plate used as force gauge, 2-moving jaw displacement gauge

action of the device. The first phase, represented in Figure 4a by the curve segment AC, refers to jaws closing movement. Second is connected with the return move of the jaw (segment CA). The mentioned graph arose in result of the n registration of test points. The work of crushing at the curve segment AC associated with one cycle, L_{ccykl}, is given as follows:

$$L_{ccykl} = \sum_{i=1}^{n}\left[\frac{1}{2}(F_i + F_{i-1})\cdot(s_i + s_{i-1})\right] \quad i = 1,\ldots,n \tag{1}$$

where F_i, s_i presented in Figure 4 were measured at n points between the boundaries, A and C.

The total crushing work, Lc, related to the material sample is equal to the sum of the work measured during consecutive working cycles:

$$L_c = \sum_{i=1}^{n} L_{ccykl_i} \quad i = 1,\ldots,n \tag{2}$$

where n is number of cycles.

During backward movement of the jaw, represented by C–A segment in Figure 4a, returning the work to the arrangement was observed. In the range of one cycle it is described by the relation:

$$L_{zcykl} = \sum_{j=1}^{n}\left[\frac{1}{2}(F_j + F_{j-1})\cdot(s_j + s_{j-1})\right] \quad j = 1,\ldots,n \tag{3}$$

where n is number of time increments.

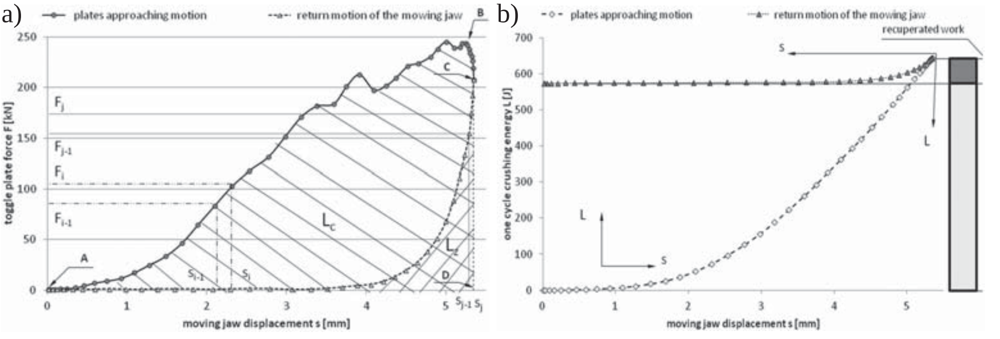


Fig. 4. Selected work cycle of crushing limestone by smooth plates a) force vs. displacement diagram b) crushing energy-displacement diagram

The total recuperated work (total) related to the given crushing process is equal to the sum of the work registered at consecutive cycles:

$$L_z = \sum_{i=1}^{n} L_{zcykl_i} \tag{4}$$

For the purposes of this work a difference of the above mentioned values was considered as the effective crushing work, $L_e = L_c - L_z$.

In Figure 4b, relation between effective and recuperated work associated to a given cycle is presented.

5. Results of the experiments

The analysis presented constitutes the certain practical values used in solving design problems of machine driving systems. In Figure 5 experimental results of the average work, based on five attempts, were presented. It shows a representation of the total work $\overline{L}_c$ (Fig. 5a), effective $\overline{L}_e$ (Fig. 5c), recuperated $\overline{L}_z$ (Fig. 5b) and specific $\overline{L}_j$ (Fig. 5d). The specific work is given as the ratio of total crushing work and the sample mass m, $L_j = L_c \cdot m^{-1}$.

Experimental works conducted showed that using the same crushing plates on different materials could litigate to the growth of the energy consumption. In the case of crushing sandstone and granite the system using a smooth and profiled plate furnished with the variable height and pitch turned out to be the best crushing set. For limestone a V-agreement of plates on the changeable scale and heights of displaced notches were advantageous.

In the Table 1 the contribution of the effective $\overline{L}_e$ and recuperated work $\overline{L}_z$ in total crushing work $\overline{L}_c$ is presented. According to the results these shares depend on the applied material strength and the shape of plates. It is possible to observe, that in the case of oblique plates, work returned to the arrangement is the biggest. It turns out, that there is a variation of the terms of the crushing process: material properties, and type of crushing plates are affecting the relationship between the recuperated, effective and total work. In the case of Morawica

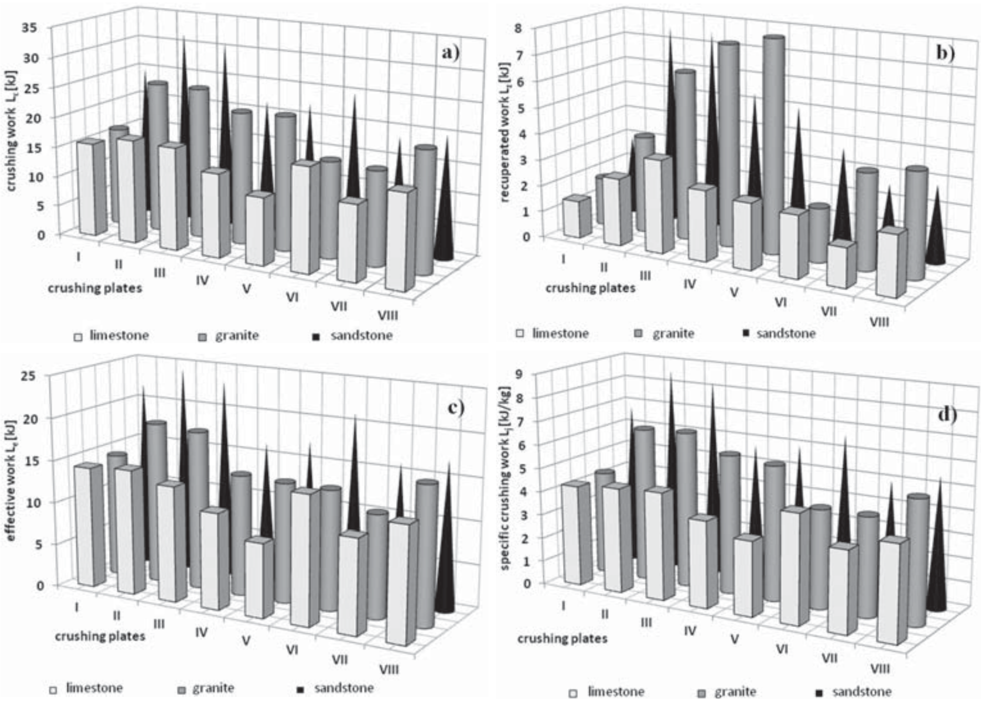


Fig. 5. Diagram of crushing energy components for tested plates: a) total $\bar{L}_c$, b) recuperated $\bar{L}_z$, c) effective $\bar{L}_z$, d) specific $\bar{L}_j$

limestone, the effective crushing work constitutes 77.6–90.9% while recuperated work shows a 9–22.4% contribution of total work. The results obtained for crushing Mucharz sandstone showed the following contributions to the total work: the effective work at a level of 76–88%

TABLE 1

Percentage contribution of the effective $\bar{L}_e$ and recuperated work $\bar{L}_z$ in total crushing work $\bar{L}_c$

Material →		Limestone		Sandstone		Granite	
Crushing plates ↓		$\bar{L}_e / \bar{L}_c$ [%]	$\bar{L}_z / \bar{L}_c$ [%]	$\bar{L}_e / \bar{L}_c$ [%]	$\bar{L}_z / \bar{L}_c$ [%]	$\bar{L}_e / \bar{L}_c$ [%]	$\bar{L}_z / \bar{L}_c$ [%]
I		90.91	9.09	88.16	11.84	88.81	11.19
II		85.09	14.91	76.35	23.65	75.92	24.08
III		79.24	20.76	75.72	24.28	74.39	25.61
IV		80.72	19.28	75.49	24.51	64.43	34.77
V		77.66	22.34	77.48	22.52	62.74	37.26
VI		86.40	13.60	85.03	14.97	87.24	12.76
VII		88.15	11.85	86.01	13.99	76.74	23.26
VIII		85.43	14.57	85.67	14.33	80.28	19.72

and the recuperated work, up to 11–24%. It also turns out, that the implementation of plates with variable height and the scale of notches (IV and V set) for crushing Strzegom granite returns an average of 36% of the total energy.

6. On verification of F. Bond energy hypotheses

The literature available presents a number of hypotheses: Kick, Rittinger, Bond, Charles, Mate, Skokołowski. The Rittinger and Bond hypotheses show certain resemblance, which consists of relating the energy of fragmenting and the change of the material area, additionally in the hypothesis of Bond the volume of grains of material grinded down is accounted. In the models formulation, material grains of identical sizes and shapes are assumed in both hypotheses.

In real processes, grain composition and curves are used, thus the hypothesis of Bond applies the grain of an 80% harmonic mean size which is accepted in the Rittinger hypothesis. This paper attempts to determine crushing energy based on the Bond energy hypothesis (this hypothesis, among others available has been showing the greatest practical significance) including curves of the grain composition of the product.

In the following discussion a brief description on the specific work of crushing is given. According to Bond the specific work is estimated:

$$L_{Bj} = C_B\left(\frac{1}{\sqrt{d}} - \frac{1}{\sqrt{D}}\right) = \frac{C_B}{\sqrt{D}}(\sqrt{n} - 1) \tag{5}$$

where:

C_B — material constant (limestone of — 140 kWh/t, sandstone of — 110 kWh/t, granite of — 110 kWh/t [12, 13]),
D — grain size of the raw material,
d — grain size of the product,
n — size reduction.

In the Figure 6 theoretical values of specific work according to relation (5) are presented. The data presented in the graph enables estimations of the crushing work consumed for the product on the given size of the sieve. By using such graphs the theoretical values of the specific work for selected samples of the entire series are introduced to Figure 6b, and compared to the experimental results. It was noticed that the suggested theoretical method charges high discrepancies. In the course of the theoretical analyses it was also observed that the method adopted to appoint the size of the product affects the results (in presented results the size of the product was appointed based on the Brach model [14]:

$$d = \frac{1}{\sum_{i=1}^{n} \frac{x_i}{d_i}} \tag{6}$$

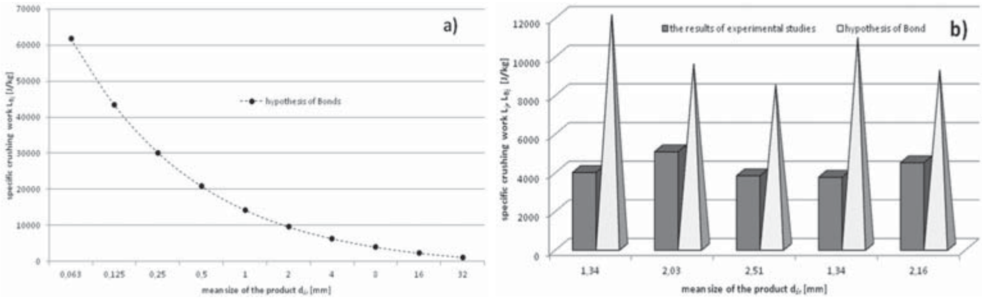


Fig. 6. Specific crushing work: a) smooth plates crushing of Morawica limestone (test I) specific work by Bond hypothesis, b) experimental results L_j and theoretical predictions of Bond specific crushing work L_{Bj}

where:

x_i — stands for percentage mass ratio of grain classes in the entire sample,

d_i — dimension of the given grain class).

As it was mentioned above the specific crushing work of the consecutive stage was estimated on the basis of the sieve analysis of the product. In Figure 7 an interpretation of the hypothesis of Bond was shown (6) relating to mass of the product selected on sieves of the screen. The data given in these two graphs enables the estimation of the specific crushing work, $L_{jTeoretyczna}$ which is the ratio of the sum of products of the specific crushing work according to Bond and mass on the given sieve to the mass of the entire sample:

$$L_{jTeoretyczna} = \frac{\sum_{i=1}^{n} L_{Bj_i} \Delta m_i}{\sum_{i=1}^{n} m_i} \tag{7}$$

where:

L_{Bji} — specific work according to Bond (estimated for the product size corresponding to the sieve test),

m_i — mass of the product associated to the given sieve size,

i — number of the sieve.

The data presented in Figure 7 describes theoretical estimations in accordance to the relationship (7) with THE results of experience referring to series presented in Figure 6b. It can be stated that current theoretical results are much closer to the experimental data than those obtained by means of the first method.

The predictions obtained theoretically are comparable to the experimental values. The graphs presented in Figure 8 describe the specific crushing work (mean value of

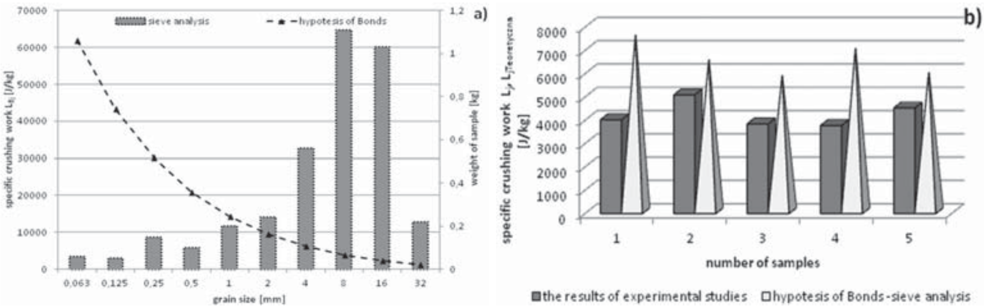
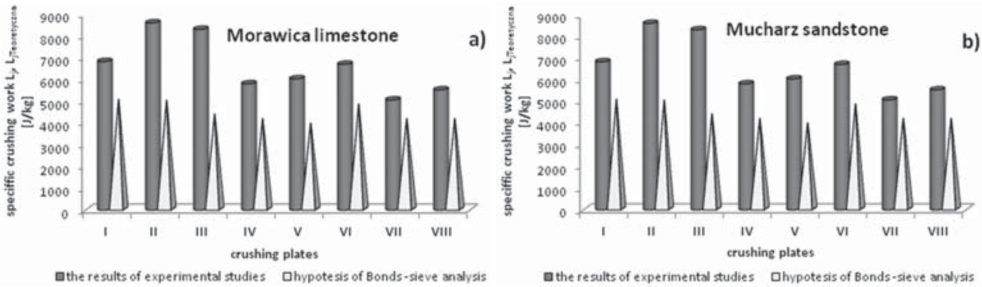


Fig. 7. Specific crushing work: a) Bond prediction diagram $L_{Bji} = f$(sieve mesh size), for Morawica limestone crushed by smooth plates (test I), b) experimental value of the specific crushing work L_j against theoretical estimations $L_{jTeoretyczna}$ based on sieve analysis



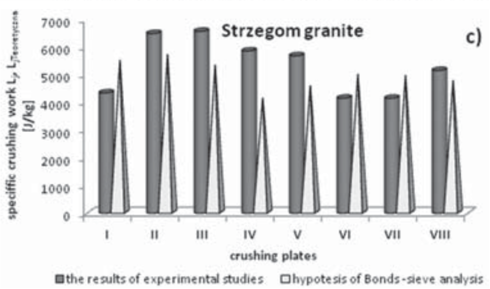


Fig. 8. Comparison of experimental and Bond predictions results of specific crushing work: a) Morawica limestone, b) Mucharz sandstone, c) Strzegom granite

five tests) depending on the arrangement of crushing plates. In the case of crushing limestone and granite experimental results are close to the theoretical predictions, showing practically admissible error approaching 35%.

7. Summary

According to the results concerning crushing energy consumption presented during previous discussion (total crushing work $\overline{L_c}$ (Fig. 5 a), specific work $\overline{L_j}$ (Fig. 5 d)) it should be stated that in the case for double toggle jaw crushers, the smooth plate combined with the variable pitch and notch height plate formulate the most advantageous set.

The minimal mean value of crushing forces [10] and crushing energy (Fig. 5) were obtained for the V set: smooth bottom plates furnished with variable pitch and height of notches (both plates mutually moved notches). Thus, plates with triangular profiles and constant pitch are less useful to studied materials.

The theoretical analysis confirmed with the results of the laboratory crusher tests the show that the application of the Bond hypothesis, including the separated fractions masses given by the sieve analysis, highly improves the precision of estimation for the specific crushing work corresponding to a chosen arrangement of plates. The results achieved suggest that the thesis of the adopted method was chosen correctly and will precisely forecast the crushing energy consumption regarding the applied arrangement of crushing plates.

The further studies of the crushing processes of minerals by different types of plates are fully justified both from a theoretical and practical point of view.

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