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Laboratory methods for combined testing of abrasiveness, grindability and wear in coal processing systems

K e y w o r d s

Abrasiveness, grindability, wear resistance.

S ł o w a k l u c z o w e

Własności ścierne, kruszalność, odporność na zużycie.

S u m m a r y

Laboratory methods were developed which involved the use of the three new rigs simulating the grinding action found in the majority of existing types of coal mills. All three rigs combine abrasion and erosion in comminution process. The objective of this investigation was to develop a tests procedure that would be suitable for general use in estimating the abrasiveness of particular coal, and to study the abrasive wear in various grinding systems. Three separate industrial problems involving coal grinding were investigated by means of the novel apparatus. The results from the relatively simply laboratory procedures, designed and operated according to the principles of similarity, may be used to predict the service life of grinding machine elements. The tribo-testing procedure and apparatus can be used to evaluate the abrasiveness of any granular coal and for testing the wear resistance of any material in abrasive or erosive action.

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Introduction

The operating cost of a coal milling plant is directly affected by the throughput rate of a fossil fuel through a mill, the power requirements of the mill, and the wear rate of the internal components of the mill. Thus, the coal properties that affect wear, such as abrasiveness, grindability, and the wear resistance of materials used for the manufacture of the grinding element, are of direct interest in this investigation. The presently available indices do not adequately describe coal properties in terms of the required information.

It is clear that there is no such thing as an intrinsic friction property of a material [1]. The same applies to other tribological material properties such as wear resistance and abrasiveness. These properties are system properties in which the given material is only one of the parameters. A carefully designed simulation in which isolated mechanical components undergo similar processes as in a complex engineering environment can only determine material performance in such a system. If the engineering environment includes processes such as abrasion and comminution, both of them must be incorporated into simulation [2], see Appendix A.

There is a complicated energy balance inside the mills during a mechanical crushing process. Crushing results in energy conversion from one form to another, including such primary energy absorbing processes as the creation of new surfaces, plastic deformation, elastic deformation, vibration and noise. In secondary energy dissipation processes, most of the energy expended in internal and external friction is converted to heat. Other factors influencing size reduction and wear processes are the distribution of coal internal weaknesses [3-6], e.g. cracks, the concentration and size of hard particles such as quartz and environmental effects, such as moisture, and the presence of chemically active gases which affect the fracture process [7-13]. Parameters affecting the grinding process can be summarised under three headings [3, 4, 14]:

1. Mineral:
   – hardness,
   – abrasiveness,
   – particle size, shape,
   – mineralogy, etc.
2. Mill:
   – mechanical properties of components,
   – microstructure of components,
   – size of mill,
   – speed of moving elements, etc.
3. Mill environment:
   – water chemistry and pH,
   – slurry rheology,
   – temperature,
   – chemically active gases, etc.

The effective action in breaking appears to be almost always tensile or shear, since compressive strength is usually greater than tensile strength, and some minerals are brittle under tension and ductile under compression. Elementary forces acting on a single grain within the majority of mills are predominantly compressive and shear. The use of compressive force in grinding machines is one of the sources of inefficiency in the comminution processes. A large number of different mills can be classified according to many criteria but the most common is classification according to purpose and principal comminuting action [3].

For the purpose of simulative testing of coal performance in comminution and abrasive/erosive interaction with grinding elements, the following classification is proposed (Fig. 1):

1. Static three-body interaction by means of direct static stressing-nipping machines, e.g. ball-race mills;
2. Low speed three-body interaction by means of inertial forces in the presence of grinding media, produced by gravity-tumbling machines, e.g. ball and rod mills; and,
3. High-speed direct impact interaction by means of inertial forces produced by mechanical means-impacting machines, e.g. hammer and beater mills.

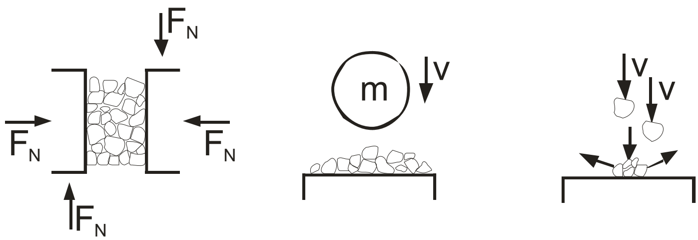

Fig. 1. Simple representation of three kinds of interactions between coal particles and grinding elements in comminution

Rys. 1. Uproszczone przedstawienie trzech rodzajów oddziaływań między cząstkami węgla a elementami mielącymi w procesie rozdrabniania

In all three classes of equipment with different mechanics of action, the tribological conditions are described by the pressure distribution, peak pressure, gradient of sliding velocity, impact speed, temperature inside the grinding zone of the mineral [15-24] and many other factors.

The procedure for adjusting the operating variables in simulated tribotesting is shown in Figs. 2-4. More accurate modelling procedures for the grinding and wear processes in all three classes of mills are presented in Refs. [22-25].

Basic mechanical properties of particulate material

The comminution process continues until all individual coal particles are small enough to leave the mill. The time taken for such a particle to be produced from the initial charge is a function of the efficiency of the mill and a property of the coal that determines the ease with which it is broken up. Empirical factors which are used at present to determine the rate at which comminution proceeds are known as the Hardgrove Index (*HGI*) and Bond Work Index, *Wi* [3, 26, 27].

The abrasiveness of a coal can be determined in a number of ways, and the traditional method for coal is based on the procedure given by Yancey, Geer, and Price [28] and described more fully in British Standard [29] as the Index of Abrasion (*AI*).

Each of these indices measures a given property of the coal, but the wear in a mill is a composite of these two separate factors, since the easier it is to crush a mineral, the less time the particle will spend in the wear process inside the mill, and the lower the abrasiveness of the mineral, resulting in a lower overall wear rate. The methods of testing presented in Figs. 2-4 combine both comminution and wear, but only in the method presented in Fig. 2 is any particle which reaches a predetermined size ejected from the grinding area through the annulus between the grinding bar holder and the stationary cylinder. In this method, the shear process is accompanied by wear of the bar. The grains of mineral become ground to a greater or lesser degree that can be determined by the index of comminution (*IC*). This index characterises the ease of pulverisation of coal. A prepared sample of coal receives a given amount of grinding energy (energy input), and the change in size is determined by sieving. The index of comminution (*IC*) of coal, for example, is expressed in milligrams of pulverised coal (fraction below 75 μm particle size) per Joule of energy input.

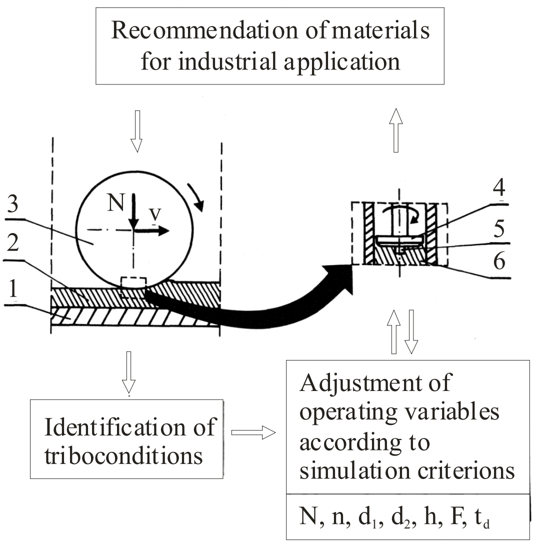

Fig. 2. Simulative tribo-testing of phenomena inside nipping mills such as ball-race within which static three-body interaction by means of direct static stressing prevails, where: 1 – bottom ring or pan; 2 – bed of coal; 3 – ball or roller; 4 – disc; 5 – bar; 6 – bed of coal

Rys. 2. Tribologiczne badanie symulacyjne zjawisk zachodzących wewnątrz młynów kulowych, w których przeważa statyczne ściskanie warstwy węgla poprzez toczące się kule, gdzie: 1 – pierścień dolny; 2 – warstwa węgla; 3 – kula albo wałek; 4 – tarcza; 5 – próbka; 6 – warstwa węgla

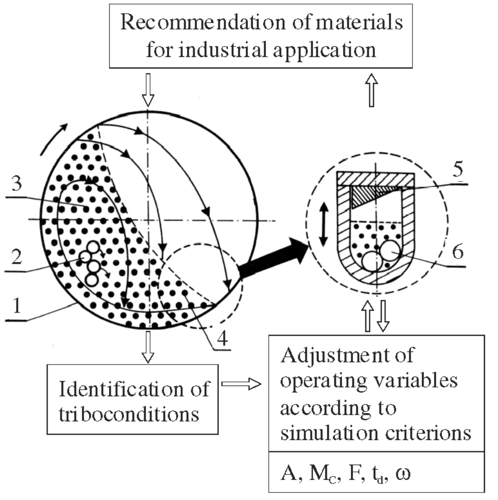

Fig. 3. Simulative tribo-testing of phenomena inside tumbling mills such as ball and rod mills within which low speed three-body interaction by means of inertial forces produced by gravity prevail, where: 1 – mill shell and lining; 2 – mill charge; 3 – tumbling zone; 4 – impact zone; 5 – lining; 6 – balls

Rys. 3. Tribologiczne badanie symulacyjne zjawisk zachodzących wewnątrz młynów bębnowych, takich jak młyny kulowe i prętowe, w których dominujące oddziaływania na warstwę węgla pochodzą od siły bezwładności ładunku w polu grawitacji, gdzie: 1 – osłona i wykładzina młyna; 2 – ładunek młyna; 3 – strefa rozdrabniania; 4 – strefa uderzenia; 5 – wykładzina; 6 – kulki

The relative displacement between the layers of particulate coal and the bar's surface provides the abrasion wear of the bar material due to coal particles sliding across the surface. They may also move relative to one another, and they may rotate while sliding across the wearing surface. In a ball-mill grinding situation, as well as in a laboratory test apparatus, the high stress abrasion occurs where the hard particles are crushed. The abrasion factor (AF) and the intensity of abrasion (IA) represent the abrasion property of coal. The abrasion factor (*AF*) is the mass of metal lost by abrasion from a carbon steel bar when rotated in a specified mass of mineral under specified conditions, expressed in milligrams of metal lost per kilogram of pulverised coal. The second parameter, intensity of abrasion (*IA*), does not include the mineral size reduction effect during the tests and is expressed in milligrams of metal lost in one second from one square meter of the bar's surface exposed to abrasive wear. Wear resistance (*WR*) and relative resistance (ε) give the best indication of the material's resistance to wear. Wear resistance (*WR*) is represented as the energy input required to wear the bar when rotated in a specified mass of coal under specified conditions expressed in megajoules of energy input per gram of metal lost. Relative wear resistance (ε) is the ratio between the wear resistance of the testing material and the wear resistance of a standard material (carbon steel). For experimental results presentation the following set of calculation formulae are used:

Wear of blade $$\Delta W = m_1 - m_2 \tag{1}$$

Energy input $$EI = 2\pi Ti \quad \text{or} \quad EI = 0.3\omega^3 A^2 M_C t_d \tag{2}$$

where $$T = \frac{1}{t_d}\int_0^{t_d} T(t)dt \tag{3}$$

Abrasion and erosion factor $$EF = AF = \frac{\Delta W}{PC}10^6 \tag{4}$$

Intensity of abrasion $$IA = \frac{\Delta W}{St_d} \tag{5}$$

where *S* is the area of blade surface exposed to wear (m^2)

Work index $$W_i = W\left(\frac{F}{F-P}\right)^{0.5}\left(\frac{P}{75}\right)^{0.5} \tag{6}$$

Index of comminution $$IC = \frac{PC}{EI}10^3 \tag{7}$$

Wear resistance of material $$WR = \frac{EI}{\Delta W}10^{-6} \tag{8}$$

Relative wear resistance of material $$\varepsilon = \frac{WR_{specimen}}{WR_{standard}} \tag{9}$$

A series of tests have been performed on nineteen coals in order to determine the parameters of interest in comminution and wear [17, 18]. Additional targets of the investigation were the comparison between various methods of testing grindability and abrasiveness of minerals, including the standard methods, and the proposed new method, as well as the determination of the properties of the most abrasive coal which was used in the following wear resistance investigation (Table 1).

The abrasiveness of the coals (*AF* and *IA*) tested in the various material configurations (standard carbon steel and chrome cast iron) show relatively different results (Table 1). Therefore, the abrasive property of a mineral should be tested with bars made from materials currently used for the balls and the races. Only those results from tests that completely simulate operational and material conditions in industrial mills can be applied directly to design calculations.

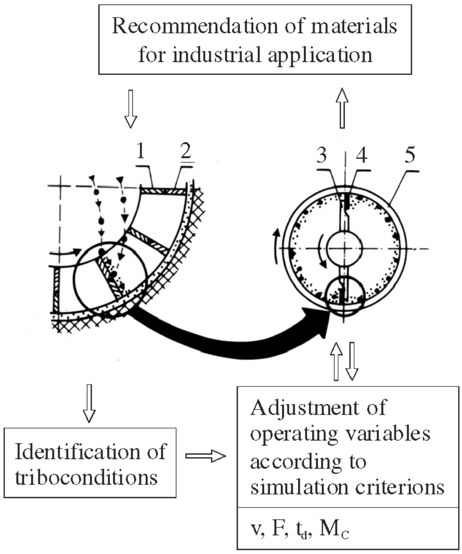

Fig. 4. Simulative tribo-testing of phenomena inside impacting mills, such as beater mills, within which high speed impact interaction by means of mechanical inertial forces prevail, where: 1 – inner beater plate; 2 – outer beater plate; 3 – rotating paddle; 4 – specimen; 5 – rotating drum

Rys. 4. Tribologiczne badanie symulacyjne zjawisk zachodzących wewnątrz młynów udarowych, takich jak młyny bijakowe, w których dominuje oddziaływanie pochodzące od dużych prędkości uderzenia i towarzyszących im sił bezwładności, gdzie: 1 – wewnętrzna płyta bijaka; 2 – zewnętrzna płyta bijaka; 3 – wirująca łopatka; 4 – próbka; 5 – wirujący bęben

Table 1. Basic mechanical properties of tested coals
Tabela 1. Podstawowe własności mechaniczne badanych węgli

No Of Coal	Quartz	Pyrite	*HGI*	*AI*	*IC*	*Wi*	Standard carbon steel		Chrome cast iron	
							AF_S	IA_S	AF_C	IA_C
	%	%	-	mg/kg	mg/J	J/g	mg/kg	mg/m^{2}s	mg/kg	mg/m^{2}s
1	0.5	0.5	60.8	5.2	0.682	1724	45	31	3.8	3.8
2	3.0	0.5	77.3	13.9	0.711	1482	141	101	12.6	12.6
3	6.2	1.5	63.9	70.2	0.895	1149	1468	1590	105.0	105.0
4	4.0	1.3	61.4	14.6	0.740	1657	181	142	16.2	16.2
5	9.0	1.5	71.0	151.5	0.876	1140	3530	3594	193.0	193.0
6	4.8	0.0	77.1	54.0	0.740	1423	903	720	81.7	81.7
7	2.6	2.5	64.6	16.1	0.452	1416	206	68	22.5	22.5
8	6.5	1.5	60.4	98.9	0.631	1343	2209	1175	152.0	152.0
9	2.7	1.5	62.2	57.6	0.806	1350	1621	1463	168.0	168.0
10	1.7	0.0	55.8	10.8	0.704	1602	92	66	13.2	13.2
11	4.3	0.0	73.5	46.0	0.816	1264	1557	1424	80.4	80.4
12	10.0	0.0	52.7	93.6	0.715	1599	1192	827	46.8	46.8
13	2.2	5.5	62.5	38.5	0.700	1469	440	328	28.5	28.5
14	6.0	1.2	68.2	67.2	0.776	1297	2027	1684	47.2	47.2
15	5.4	0.0	65.7	58.5	0.892	1150	1092	1126	82.4	82.4
16	5.7	0.0	66.4	48.1	0.759	1452	1153	840	45.0	45.0
17	15.5	70.1	70.1	55.0	0.741	1244	660	492	45.4	45.4
18	7.0	68.1	68.1	31.5	0.844	1255	719	679	66.6	66.6
19	8.0	49.0	49.0	18.8	0.747	1522	135	110	10.7	10.7

Some considerations on abrasive wear in comminution

Abrasive wear is the major form of wear on mill components. This form of wear is usually caused by hard mineral particles that produce no significant adhesion and seizure phenomena during the course of wear. The large variety of shapes and mechanical properties of the abrasive particles (e.g. quartz and pyrite particles in coal) and diverse loading conditions give rise to variable stresses at contact [30-32].

Wear debris is generated as a result of a single or multiple action of the abrasive agents, i.e. microploughing, microcutting, microcracking, and microfatigue [33-37]. This diversity of wear processes and conditions results in various combinations of the elementary processes involving the disintegration and loosening of the surface layers.

Since the abrasive wear process is complex and varies from one situation to another, it is impossible to design a universal abrasive wear tester. Consequently, many specialised testers have been developed. For abrasive wear, testers have been designed by Khruschov [34] and others [37-40].

In spite of the wide variety of testers, there was a demand for a new apparatus simulating conditions in various mill designs which combine both abrasion and comminution processes. The objective of this investigation was to develop a test procedure that would be suitable for general use in estimating the abrasiveness of particular minerals, and to study the abrasive/erosive wear in various grinding systems (Figs. 2-4).

Three separate industrial problems involving coal grinding were undertaken by means of three novel design apparatus. The results from tests and discussion are presented below.

Testing Wear Resistance of Materials in a Predominantly Static Three-Body Interaction

Conditions within a large-size vertical ball-race mill were simulated in this series of tests by means of the apparatus (Figs. 2 and 5) designed by Ścieszka [17], [18]. The highly abrasive coal No 5 (Table 1) was used in all tests. The group of materials tested consisted of five hard cemented tungsten carbides, one standard carbon steel, and one high chrome cast iron, CI (Table 2) currently used for rings in ball-race pulverises. The decision to select this set of materials was based on significant success achieved in a casting process that metallurgically bonds exceptionally hard cemented tungsten carbides to tough 4330 base steel [41]. This casting process reduced excessive wear problems in some severe operating conditions and could be applied to the manufacture of the grinding elements.

The tribological conditions, which are generated on the bottom surface of the rectangular bar (Fig. 5), simulate conditions on the ball-coal layer interface inside ball-race mills [22] and [23]. Hence, the results obtained from the tests can be applied directly to predict the material performance in industrial pulverises. The results are summarised in Table 2. Most of the cemented tungsten carbides gave excellent wear resistance.

With material grade No 3, wear resistance was increased 658 times compared with the standard material and 26 times compared with the high chrome cast iron presently used for casting race.

Table 2 includes additional parameters such as hardness, relative impact resistance, and optional parameter β.

$$\beta = \varepsilon\, \alpha\, 10^{-3} \tag{10}$$

where: ε is relative wear resistance

α is relative impact resistance. (The data presented in Table 2 were taken from Ref. [41] that includes the drops weight test method definition).

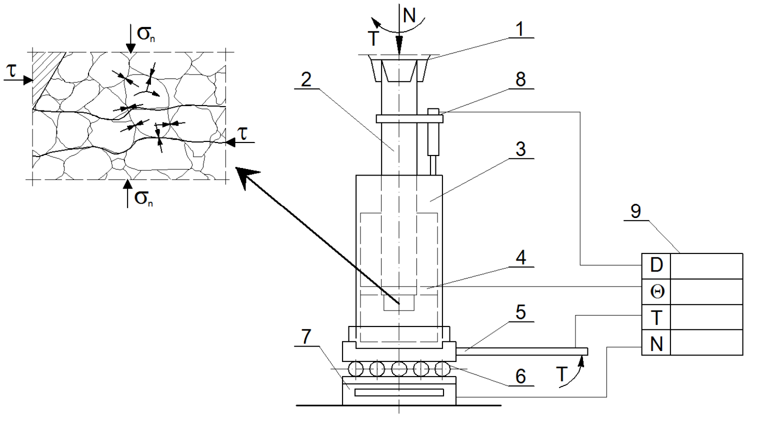

Fig. 5. Schematic diagram of apparatus, and interpretation of interaction between the particulate mineral and the bar within the shear zone, where: 1 – drill chuck; 2 – drive shaft; 3 – cylindrical chamber; 4 – thermocouple; 5 – torque indicator; 6 – thrust bearing; 7 – force indicator; 8 – displacement indicator; 9 – recorder

Rys. 5. Schemat urządzenia i objaśnienie oddziaływania między cząstkami mineralnymi a próbką w strefie ścinania, gdzie: 1 – uchwyt wiertarski; 2 – wałek napędowy; 3 – komora cylindryczna; 4 – termopara; 5 – wskaźnik momentu obrotowego; 6 – łożysko oporowe; 7 – wskaźnik siły; 8 – wskaźnik przemieszczenia; 9 – rejestrator

Parameter β is based on the assumption that the relative wear resistance and relative impact resistance are an equally important property of material when considering the application of materials for casting mills' race. Applying parameter β as a criterion, the grade No 3 was chosen and recommended as a filler for the composite cemented tungsten carbide 4330 base steel rings. This indicates that the optimal percentage of binder for a given range of sintered carbides and tribo-conditions was about 12 percent (Table 2).

Table 2. Mechanical properties of bar materials
Tabela 2. Własności mechaniczne próbek materiałów

No	Material composition		Wear	Wear resistance MJ - 9	Relative wear resistance	Vicker's hardness HV_{30}	Relative impact resistance α	β
	Material grade	Co Binder						
		%	μg/rev					
1	Carbon Steel, CS	-	74.00	1.18	1.0	134	188	0.2
2	Cast Iron, CI	-	3.10	29.10	24.7	746	125	15.6
3	Cemented WC-Co	12.2	0.14	776.00	658.0	1210	100	65.8
4	Cemented WC-Co	8.8	0.18	623.00	528.0	1310	71	37.5
5	Cemented WC-Co	20.0	0.78	128.00	108.0	897	100	10.8
6	Cemented WC-Co	6.0	0.13	808.00	685.0	1501	25	17.1
7	Cemented WC-Co	7.0	0.16	666.00	564.0	1717	12	6.8

Testing Grinding Properties of Coal in a Predominantly Tumbling Condition

In tumbling mills, the predominant mechanism of comminution is crushing, due to the low speed impact and tumbling action of the charge. In the simplified horizontal tube mill arrangement shown in Fig. 3, the mechanical conditions are described by the interaction between the charge and the mill's inner surface and also by the interaction within the charge. Considering the origin of wear and size reduction processes in the impacting machine, the peak maximum pressure p_{max}, similarity criterion was used.

$$p_{max} = 0.265(E^9\ R^{-6}\ V^4\ m^2)^{1/10} \quad (11)$$

where: E – reduced modulus (GPa)
R – radius of curvature (m)
V – speed of collision (ms^{-1})
m – mass of ball (kg)

The applied model is based on the Hertz impact theory [43].

The proposed method, which simulates the impact action in the tube mill, involves the use of an electromagnetic vibrator (EMV) and chamber with the two balls inside, shown in Fig. 3. The energy input absorbed by the grinding system is given by Equation [44]:

$$EI = 0.3\ \omega^3\ A^2\ M_c\ t_d \tag{12}$$

In each test, a charge of 30 g of coal sieved through a 600-1200 μm sieve, together with two steel balls, was placed inside the chamber. The grinding action was performed by the balls impacting against the sides of the chamber and against each other. In order to create a sliding component of the compound impact action, the chamber cover, simulating a mill liner, was tilted as shown in Fig. 3.

Since the grindability and abrasiveness of minerals are not their inherent properties but a grinding system property, it is necessary to obtain a set of suitable conditions in which to run the tests, and to keep them constant for each test on all the mineral samples. In this way, the final results can be directly compared to obtain the order of grindability, abrasiveness, and wear resistance of materials used for the production of balls and liners. In this part of the investigation, the frequency (n = 50Hz) and the amplitude (A = 0.005 m) were fixed based on the similarity of the kinematic collision energy in the laboratory rig and the actual mill.

A series of tests was conducted on the five coals. The results are presented in Figs. 6 and 7. Figure 6 is of special interest, because it shows that coal samples respond inversely to the two grinding methods (nipping and tumbling) with a high correlation coefficient of 0.983. Those coal samples poorly ground by nipping could be ground better by tumbling, because they respond well in comparison with the other samples to this kind of grinding.

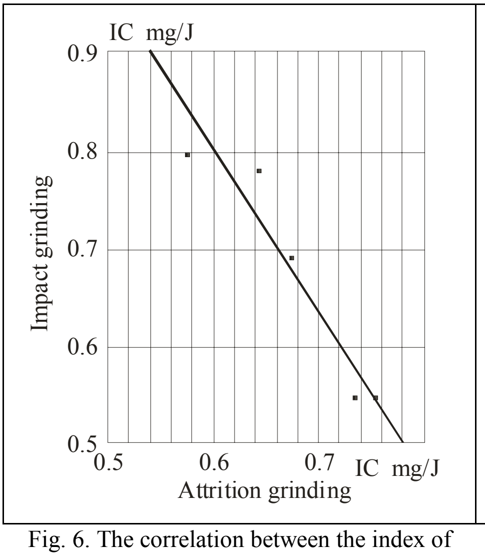

Fig. 6. The correlation between the index of comminution (IC) in two different grinding systems for five coals

Rys. 6. Zależność między wskaźnikiem rozdrabniania w dwóch różnych systemach mielących dla pięciu węgli

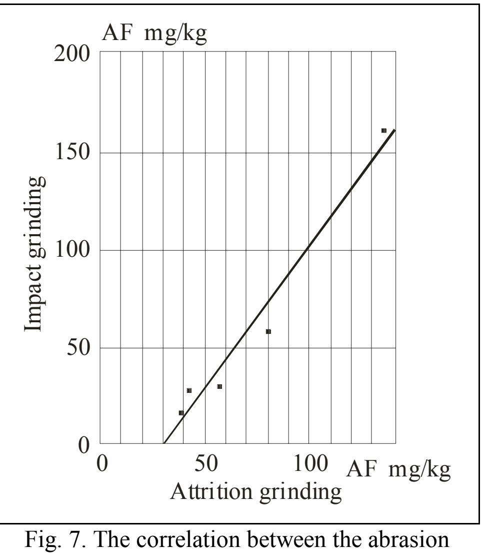

Fig. 7. The correlation between the abrasion factor (AF) in two different grinding systems for five coals

Rys. 7. Zależność między współczynnikiem ścieralności w dwóch różnych systemach mielących dla pięciu węgli

Testing Wear Resistance of Materials in a Predominantly High Speed Impact Interaction

In order to simulate as closely as possible the tribological conditions inside a coal impact beater mill, a high-speed erosion tester was constructed [25]. The construction of this tester is shown in Fig. 4. In the type of impact mill that this rig simulates, the coal enters axially and changes its flow direction to a radial one inside the mill. The area of impact of coal grains with the beater plate depends on the position of the coal entry to the mill. The area of direct impact is equivalent to the inner beater plate in Fig. 4.

The grinding intensity depends mainly on the impact stress in the coal grain contact area with the beater plate and on the number of contacts. The impact stress depends on the impact velocity. In the full-scale mill analysed, the peripheral speed was about 100 m/s, which was sufficient for grinding soft coals such as lignite. Wear during the comminution of lignite was characterised by deep grooving due to hard mineral impurities such as quartz and pyrites.

Although erosive wear has a stochastic character determined by random particle dynamics, the worn material is removed by a combination of simple local processes such as cutting, ploughing, cracking and surface and sub-surface fatigue. The relative contribution of each process to the overall wear rate depends mainly on the material hardness and fracture toughness, and it can be classified as either brittle or ductile wear.

In the region equivalent to the outer plate, wear is less intense, because it is caused only by sliding erosion without direct impact. In this region, the predominant wear mode is low stress scratching, mainly cutting or ploughing, by hard mineral fragments of coal below their crushing strength. It was postulated that the two distinct regions of predominantly impact, and predominantly sliding erosion, together with the size reduction process could be modelled in relatively simple laboratory experiment.

The rig shown in Fig. 8 consists of two counter-rotating components, a shaft onto which two specimens are attached, and a drum. The rotational speed of the drum and the shaft were 3000 revolutions per minute giving a relative velocity of 6000 rpm and peripheral speed of about 100 m/s. The specimen front faces were worn by impact erosion, the external face being worn predominantly by sliding erosion. The test duration was selected to simulate the time taken for the coal in the full-size mill to be comminuted to the desired size. The test duration was five minutes for all tests.

The erosion was determined by the erosion factor EF that was calculated from the following equation:

$$EF = (\Delta W/PC)\ 10^6 \text{ mg/kg} \tag{13}$$

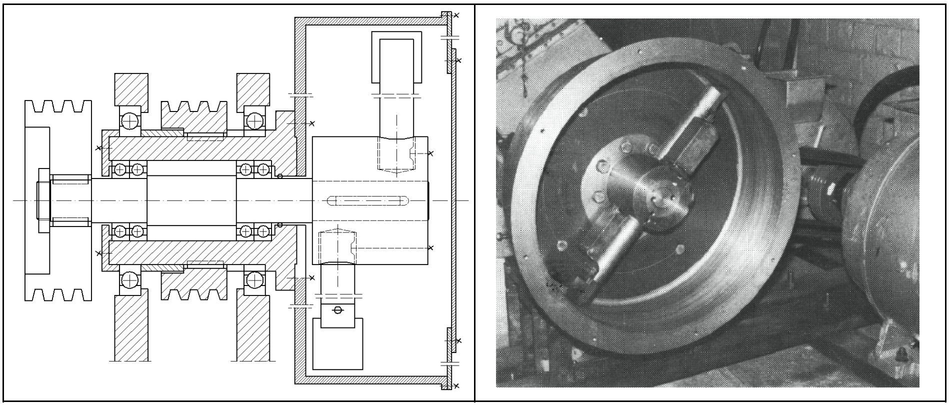

Fig. 8. Overall view of the high speed impact tester
Rys. 8. Ogólny widok testera o dużej prędkości uderzenia

The relative erosion resistance (ε) of each material was calculated by dividing the erosion factor for the least erosion resistant specimen by the erosion factor of the material considered.

The results are summarised in Table 3. These results allow the specimens to be classified according to their resistance to the type of wear that takes place on the beater plates.

Table 3. Relative erosion resistance of various metals tested in the impact rig
Tabela 3. Względna odporność na ścieranie różnych metali badanych w urządzeniu udarowym

Spec. No	Material	*EF* mg/kg	E
1	25Cr cast iron (martensitic)	51.7	14.20
2	12Cr tool steel	275.9	2.66
3	12Mn steel	540.2	1.36
4	Carbon tool steel	734.9	1.00

The results suggest that the life expectancy of the beater plate could be increased by up to 14 times by using the 25 percent chrome cast iron instead of the carbon tool steel originally used or by a factor of 2.5 by using the 12 percent chrome steel.

Conclusions

Three types of apparatus have been developed to study the abrasive wear of materials in friction contact with mineral particles during the comminution process and grinding properties of granular coal. The equipment has a wide pressure and velocity range and can be used to simulate tribo- conditions inside various types of mills.

The test procedure developed in the course of this work may not be refined sufficiently in its present form for general use, but it may serve as a starting point from which an acceptable test procedure can be developed. So far this method has been used on nineteen coals. Only wider use of the procedure by other investigators and correlation with many plant experiences can determine to what extent the method will have to be modified to render it suitable for general application.

The abrasion factor and intensity of abrasion can be applied in the calculation of the service life of the rings. In this case, the results from a relatively simple laboratory apparatus, designed and operated according to the principles of similarity, may be used to predict the service life of machine elements in industry. The simulative tribo-testing procedure and rig can be used to evaluate the abrasiveness of any granular mineral and for testing the wear resistance of any material in any abrasive action.

The rigs described are an attempt to simulate as accurately as possible the wear mechanism and size reduction processes inside the full-scale equipment in a laboratory size rig.

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APPENDIX A

Concomitant Effects in Comminution

Simple tests were conducted on a specially designed apparatus to determine a correlation between particle comminution and abrasion wear. A comparison was made between results obtained without the bar and with the bar fixed to the underside of the disk (Fig. Al). Highly abrasive coal No 5 and low abrasive coal No 1 are described elsewhere and were used for the analysis shown in Table 1 were used. In all tests, the same normal load, N=2000N, number of revolutions, i=400 and rotational speed, n=100 min^{-1} were applied. Every test was repeated four times. The average values are presented in Table Al.

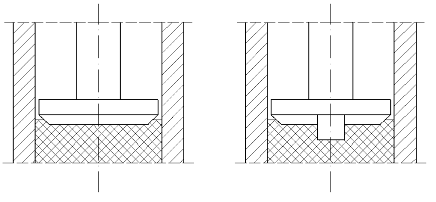

Fig. A1. Shaft-disc assembly with and without a bar
Rys. A1. Układ wałek-tarcza z próbką i bez próbki

Results indicate that wear was significantly affected by the presence or absence of the bar. The tests conducted without the bar closely represent two-body abrasion in which interlocked particles under compression are sliding upon a rotating disc with only little shearing, rotation, and consequently, little particle crushing.

The test with the bar, on the other hand, represents three-body abrasion in which particles in contact with the bar are being continuously redistributed by shearing action. This action guarantees that, in every revolution, a different particle layer is in contact with the bar, and the bar surface is attacked by new sharp edges just created in the shearing/crushing process.

It is clear from parameters such as AF (Table Al) that wear is closely correlated with the size reduction processes.

Table A1. Comparative results from grindability-abrasion test
Tabela A1. Wyniki porównawcze z badania kruszalności i ścierności

Property	Highly Abrasive Coal		Low Abrasive Coal	
	Without Bar	With Bar	Without Bar	With Bar
ΔW [g]	0.002	0.0472	0.0001	0.0016
PC [g]	0.760	16.80	0.45	10.80
EI [J]	17700.0	36260.0	25200.0	31500.0
AF [mg/kg]	2631.0	2809.0	222.0	148.0
IA [mg/m^2g]	63.0	1479.0	3.0	50.0

This correlation can be attributed to the creation of new sharp edges during the crushing of particles, as well as, but to a lesser degree, to sudden release of elastic energy after particle collapse. This simple experiment shows the inter-relation between abrasion and comminution and emphasises the difference between two-body and three-body abrasion. If, in a practical tribo-engineering system, three-body abrasion prevails, it must not be simulated by means of a laboratory two-body abrasive test system.

Nomenclature

A	– amplitude (m)	p	– pressure (MPa)
AF	– abrasion factor (mg/kg)	P	– product size modulus (μm)
AI	– index of abrasion (mg/kg)	PC	– pulverized fraction of coal below 75μm (g)
d_1	– diameter of disc (m)	R	– radius (m)
d_2	– diameter of cylinder (m)	S	– area of surface (m^2)
EF	– erosion factor (mg/kg)	t	– time (s)
EI	– energy input (J)	t_d	– duration of test (s)
F_N	– normal force (N)	T	– average integral value of torque (Nm)
F_T	– tangential force (N)	v	– velocity (m/s)
F	– feed size modulus (μm)	W	– work input (J/g)
H	– height of bar (m)	W_i	– work index (J/g)
i	– number of revolutions	ΔW	– wear of blade (g)
IA	– intensity of abrasion ($mg/m^2 \cdot s$)	WR	– wear resistance (MJ/g)
IC	– index of comminution (mg /J)	α	– relative impact resistance
m	– mass (g)	ε	– relative wear resistance
m_1	– initial mass of blade (g)	σ_c	– compressive strength (MPa)
m_2	– final mass of blade (g)	σ_n	– normal stress (MPa)
M_C	– mass of charge (kg)	τ	– shear strength (MPa)
N	– rotational speed (min^{-1})	ω	– angular velocity (rad/s)
N	– normal force (N)		

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Metody laboratoryjne do łącznego badania własności ściernych, kruszalności i zużycia w systemach przeróbki węgla

S t r e s z c z e n i e

Opracowano metody laboratoryjne, które dotyczą wykorzystania trzech nowych testerów symulujących proces mielenia, jaki zachodzi w większości typów istniejących młynów węglowych. Wszystkie trzy testery łączą ścieranie i erozję z rozdrabnianiem. Przedmiotem tego badania było opracowanie procedury badań, która nadawałaby się do powszechnego stosowania w szacowaniu własności ściernych określonego węgla i do badania zużycia ściernego w różnych systemach mielących. Za pomocą nowej aparatury badano trzy odrębne problemy przemysłowe dotyczące kruszalności węgla. Wyniki z relatywnie prostych procedur laboratoryjnych, zaprojektowanych i przeprowadzonych zgodnie z zasadami podobieństwa, mogą być wykorzystane do prognozowania trwałości eksploatacyjnej elementów młynów węglowych. Tribologiczne procedury badawcze i aparatura mogą być wykorzystane do oceny własności ściernych dowolnego węgla i do badania odporności na zużycie dowolnego materiału konstrukcyjnego pracującego w warunkach dominującego procesu zużycia ściernego lub erozyjnego.