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Change of mechanical properties of coal during subsequent combustion phases

In this paper an attempt to describe the change of mechanical properties of coal which takes place during the combustion process has been made. These changes are of essential significance in the comminution process which occurs simultaneously in the combustion chamber. The comminution is of particular importance during the combustion in the fluidized bed conditions where in the opinions of many authors, it is one of the sources of generating the loss of incomplete combustion. An analysis of the change of mechanical properties on the basis of three parameters i.e. compression strength, Vickers hardness and fracture toughness was carried out. Steam coal type 31.2 from Sobieski mine commonly applied in pulverized boilers as well as in fluidized boilers was chosen for the purposes of research. The research was carried out using specially prepared cubical coal particles with measurements of 15 x 15 mm. Analysis was run on raw coal and for all combustion phases also, i.e. after heating and drying, after devolatilization and volatile combustion and during char combustion. The results obtained clearly pointed towards the weakness of the coal structure along with the combustion process. The biggest weakness of the coal structure was noted after volatile combustion at the moment of the ignition of char. The measured values of hardness and fracture toughness can be used to model the mass loss of coal particles in the conditions of the fluidized bed particularly in the upper dilute zone.

Nomenclature

A_z	–	surface area of a char, m^2
C_{0_2}	–	oxygen concentration, kg/m^3
Cv	–	concentration of inert material, m^3/m^3
Gs	–	flow rate of inert material, kg/m^{2}s
HV	–	hardness, N/m^2
k	–	reaction rate constant, m/s
K_c	–	fracture toughness, Nm$^{-3/2}$
m_a	–	mass of ash, kg
m_k	–	mass of char particle, kg
t	–	time, s
u	–	velocity of inert material, m/s

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Greek symbols

ρ_k	–	density of char, kg/m^3
Ω	–	stoichiometrical coefficient, –

1 Introduction

The specificity of fluidized combustion depends on the combustion of fossil fuels in conditions of the fluidized bed. The fuel particles after insertion into the combustion chamber collide with inert material during the entire course of their presence in the combustion chamber, whereby the inert material initially forms quartz sand particles and ash particles generated from the incombustible part of fuel. As a result of contact between the particles of inert material and the mother fuel particles, fine particles < 100 μm [1] are ripped off from the main part. This process is defined as the erosion process and plays an important role in both the combustion process in which it is responsible for the accelerated loss of combusted particles, as well as increasing the loss of incomplete combustion as the fine coal particles formed in the upper zone of combustion chamber are elutriated to the cyclone where due to their excessively small diameters are passed on to the next sequence. The precise description of the erosion process seems to be really essential in order to completely understand the combustion process taking place in the conditions of the fluidized bed, as well as limiting the loss of incomplete combustion. The erosion process has been the subject of analysis for many scientific centres, whose aim was the determination of the susceptibility of fuel particles to mechanical attrition and their correlation mainly with the hydrodynamics of the combustion chamber [2–8]. It was accepted that the tendency of coal to generate fine solid material can be expressed by means of the semi-empirical attrition rate constant k [7]. Its values are strongly related with the combustion process and for mechanical attrition at a range of $(0.05–0.31)\times10^{-7}$ and in combustion assisted attrition in the fast bed at a range of $(0.5–5.0)\times10^{-7}$. Its value depends not only on the properties of coal but also on the conditions of the experiment, the temperature of the process, the fluidized bed, the diameter of particle, the contents of O_2 and the fluidization regime. In the opinion of many authors [7,8] it is difficult on the basis of the value of k only to assess the influence of the coal properties on the level of the erosion process during the fluidized combustion. Moreover, it has been stated that the key process determining the level of the erosion process on the particles of the coal surface in the fluidized bed is the process of weakening the external structure of coal as a result of the combustion process. This regularity was also confirmed by the tests conducted by Pelka [9] for the case of Polish energy coals. The author in question confirmed the close correlations of the attrition constant rate with the combustion process and obtained the difference described at two orders of magnitude. The proposed numerical model of mass loss [10] according to the Eq. (1) for fast fluidization which takes place in the upper zone of combustion chamber correctly expresses the real mass loss. The condition of obtaining the correct results is first of all, the knowledge of two strength parameters of coal determining according to the authors [11] its susceptibility to mechanical comminution as a result of the collision of fuel particles with the material of the fluidized bed. These parameters are as follows: Vickers hardness HV and fracture toughness K_c. Thus, the aim of the research is the experimental determination of both parameters and additionally, the compression strength in the whole field of the combustion process:

$$\frac{dm_k}{dt} = \begin{cases} -A_z k C_{0_2}\Omega - \rho_k \dfrac{HV}{K_c^2} m_k \left[\sum\limits_{i=1}^{n} Cv_i u_i^3\right] & \text{for} \quad m_k > m_a \ , \\ -\rho_k \dfrac{H}{K_c^2} m_k \left[\sum\limits_{i=1}^{n} Cv_i u_i^3\right] & \text{for} \quad m_k \le m_a \ . \end{cases} \tag{1}$$

2 Test stand and methodology

In the research conducted, an analysis of the change of the mechanical properties of hard coal type 31.2 from Sobieski mine was carried out. The basic condition necessary to be fulfilled during the strength tests, especially static compression strength, is to maintain the same shape of the coal particle tested. This condition is very difficult to fulfill and in the case of some coal types, this is just impossible. During the course of heating the said particle in the first stage of combustion where the rate of heating may vary from 100 °C/s to more than 1000 °C/s [1], as well as during the intensive devolatilization process, most hard coals undergo primary fragmentation and disintegrate into a few smaller particles of the same scale of size. Moreover, some groups of coal show the tendency towards swelling and take on an indefinite shape, thus rendering it impossible to conduct the planned strength tests in the research analysis. One of the few coal types which fulfilled the condition of shape constancy was that of the coal from the Sobieski mine which was accepted for analysis. The results of proximate analysis are presented in Tab. 1.

The combustion process was carried out using the test stand whose scheme is shown in Fig. 1. The coal particles were inserted into the combustion chamber by means of a mobile system where the tested particle was placed on the handle of an extensometer branch scale. The combustor chamber was equipped with a sight

Table 1. The results of proximate analysis of tested coal.

Coal type	Mine	Technical analysis				
		Volatile matter	Moisturer	Ash	Fixed carbon	Lower heating value
		%	%	%	%	kJ/kg
31.1	Sobieski	28.91	10.8	11.07	49.94	23488

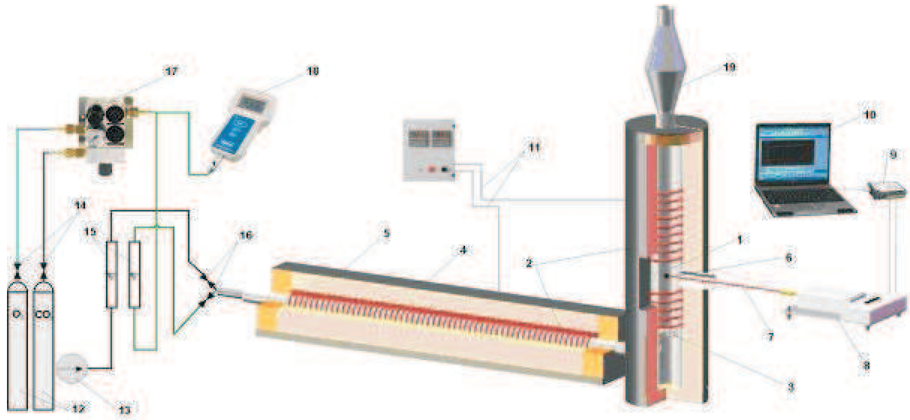

Figure 1. Schematic diagram of the test apparatus. 1 – combustion chamber, 2 – heating elements, 3 – air distributor, 4 – air preheater, 5 – thermal insulation, 6 – coal particle, 7 – S-type thermocouples, 8 – laboratory scale, 9 – measuring card, 10 – computer, 11 – system of regulating and measuring temperature, 12 - gas cylinders, 13 – air compressor, 14 – pressure regulators, 15 – rotameters, 16 – flow regulating valves, 17 – gas mixer, 18 – oxygen analyser, 19 – ventilation duct.

glass made from quartz glass which enabled the observation of the combustion process during its entire course.

As the aim of the work was the determination of the chosen strength parameters of coal in all phases of combustion, it was therefore necessary to break the combustion process down into all its stages. The particles with relation to the strength tests after drying, i.e after the first stage of combustion was according to the Polish norm (PN-80/G-04511) in a separate heating chamber. The other coal particles during the next three phases as a result of breaking up the process on the basis of the mass loss observed on the branch scale, as well as the observation of the process through the means of the sight glass. The strength tests in the range of three chosen parameters in all the phases were carried out using a series of 10 particles for each parameter separately. The final result by means of averaging the individual results was obtained.

The tests on the coal samples encompassed the following:

- static compression strength, (determination of the maximum force),
- Vickers hardness,
- fracture toughness by means of the stress intensity rate.

Static compression strength and fracture toughness were realized for cubic coal particles with measurements of 15 x 15 mm. These tests were carried out by means of a servo-hydraulic testing machine. The velocity of compression was 0.02 mm/s. Moreover, in the case of raw coal, tests were run parallel and perpendicular to the coal lamination (Fig. 3). However, the measurement of hardness by means of the hardness testing machine- Future Tech FV-700, was carried out to comply with penetrator loading 10 kG (98.07 N). In the case of coal after burning out, the volatile matter due to the high level of brittleness required a lower penetrator loading of 3 kG, 1 kG and also 0.05 kG to be used for the measurement of hardness.

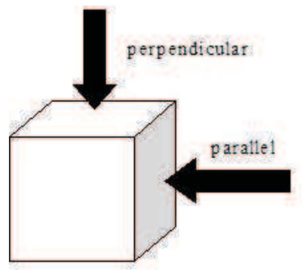

Figure 2. The scheme of compression in two planes.

3 Results

3.1 Static compression strength

The first stage of the research was to conduct a static compression of a chosen coal type and determine the maximum destructive force. In Tab. 2 the results obtained in the next combustion phases are presented. The said results clearly

Table 2. Results of compression of coal particle in the different phases of combustion.

Coal phase	Maximum force F [N]	Mean value / Standard deviation
raw	6583	5496.0/1256.55
after drying	3325.11	3195.26/129.85
after combustion volatile matter	260	158.5/101.5
after 60 s of char combustion	267	205.5/61.5

indicated the significant strength changes occurring during the combustion process. As a result of the drying process, the maximum force decreased by as much as half, which shows the weakness of coal structure together with the decreasing level of moisture in the coal. The biggest change was noted in the case of coal after the volatile matter included in the particle burnt out. This difference is 3065.11 N, which means that the weakness of the coal structure with relation to raw coal was at a ratio of over 25 times. In the last phase of coal combustion, i.e. after the next 60 s of char combustion, it was stated that the maximum force during the compression test stabilizes at a similar level. The test for maximum force after a time period of longer than 60 s was not possible due to the bigger change of particle structure as a result of its combustion. The results presented point towards the smallest mechanical strength of coal after the volatile matter burns out at the moment of ignition of the char.

It should be stated that the standard deviation obtained for individual combustion phases of the analyzed parameter were in some cases over 50%. This discrepancy to a large degree results from the variable coal lamination. For this reason, it has been decided to determine the maximum force acting on a perpendicular and parallel axis to the coal lamination. The results of this test are

Table 3. Results of compression of coal particle perpendicular and parallel to coal lamination.

Direction of coal compression	Maximum force F [N]	Mean value / Standard deviation
perpendicular	7921	5736.5/2239.5
parallel	3609	3397.33/268.73

presented in Tab. 3. On the basis of the said results, we can state that the mechanical properties of coal are anisotropic and depend on the lamination direction. The difference of maximum compression force can achieve even 100%. Moreover, it should be noted that the standard deviation for the perpendicular direction registered is also high which may result in difficulty with determining the lamination direction and also the variation of lamination inside the coal. In further tests, in the subsequent combustion phases the same perpendicular loading direction was established.

3.2 Measurement of hardness

The second parameter determined within the confines of the realized work was Vickers hardness *HV*. This parameter according to Ghadiri i Zhang [11] is equal to the fracture toughness K_c in terms of the essential parameter in describing the susceptibility of brittle material to comminution as a result of the collision of particles. Until now in the modelling of the comminution process the hardness of raw coal at an ambient temperature was accepted depending on the carbon content [10], i.e. in the case of coal tested from the Sobieski mine type 31.2 $K_c = 0.25 \times 10^9$ N/m^2. On the basis of the results obtained (Tab. 4), it should be stated that the accepted value for raw coal was correct but for the purposes of modelling, the mass loss of a char this value should be reduced as it changes fundamentally in reality to the level $K_c = 0.06 \times 10^9$ N/m^2. The tests carried out, as in the case of the static compression test point, indicate the biggest decrease of mechanical strength of coal after the process of burning out the volatile

Table 4. Coal hardness in all phases of coal combustion.

Coal phase	HV10$\times 10^9$ [N/m^2]	Mean value / Standard deviation
raw	0.2158	0.1864 / 0.021
after drying	0.1782	0.1684/0.0094
after combustion of volatile matter	0.0618	0.0618
after 5 s of char combustion	0.0351	0.0351
after 10 s of char combustion	0.0713	0.05895/0.012
after 15 s of char combustion	0.0713	0.0713
after 25 s of char combustion	0.0601	0.0502/0.0099

matter included in the coal from the moment of char ignition. The drying process weakened its hardness to a small extent. The mean values obtained are on the same level and the standard deviation indicates the high level of repetition of the results at hand. The hardness tests were conducted perpendicular to the coal lamination. The determination of hardness of the char after 60 s was impossible due to the degradation of coal structure, usually its delamination as shown in Fig. 3. Thus, it was decided to measure the level of hardness after shorter time periods, i.e.: 5, 10, 15 and 25 s.

Figure 3. Delamination of coal particles after 60 s of combustion process.

3.3 Fracture toughness K_C

The fracture toughness rate according to the Klepaczko method [12] was determined and the tested particle was characterized by the following geometry: $H = 38$ mm, $B = 38$ mm, $W = 32$ mm, $a = 5$ mm oraz kąt $\alpha = 45°$. The particles prepared for testing are presented in Fig. 4. The values of the fracture toughness rate for raw coal from the Sobieski mine after drying, as well as after the volatile matter burning out are presented in Tab. 5. Due to the excessively large changes in the particle structure and its fragmentation, the determination of the fracture toughness rate during char combustion was not characterized (Fig. 5). It should be noted that the particles used in this section of the test were large in size according to the Klepaczko procedure, i.e. 38/38/32. In the case of such large quantities of particles the time of the combustion process of the volatile matter is long and amounts to 400 s. For this reason, the char combustion phase

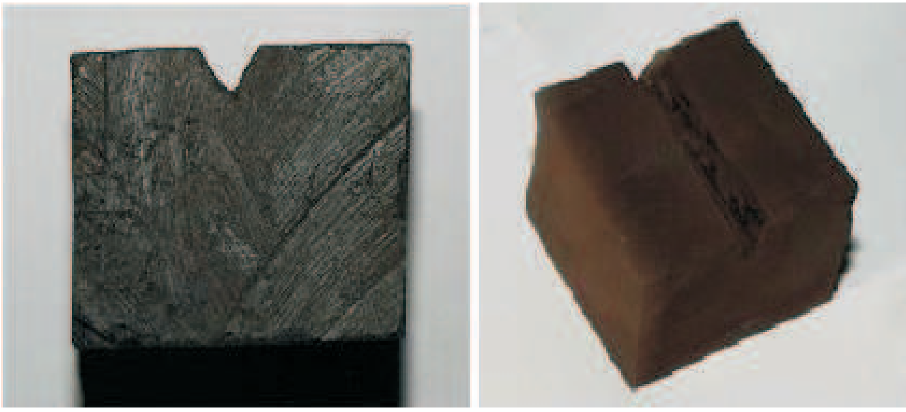

Figure 4. Hypothetical coal particles from Sobieski mine prepared for testing the fracture toughness rate.

Table 5. Fracture toughness rate for coal in all combustion phases.

Coal phase	K_C, [MPa$\sqrt{m}$ ($\times 10^6 Nm^{-\frac{3}{2}}$)] (maximum value)	Mean value/ Standard deviation
raw	0.2814	0.1891/0.083
after drying	0.6728	0.4490/0.2005
after combustion of volatile matter	0.07537	0.05381/0.04517

begins long before the completion of the process of combusting the volatile matter as indicated in Fig. 6. It can be recognized that the obtained values of fracture toughness after the volatile matter burning out have very similar values to the real value of the fracture toughness rate in the phase of char combustion.

The results obtained suggest that the type of coal particle tested without moisture clearly increases its resistance to cracking and in connection with this fact, decreases its level of brittleness. This means that without the combustion process of the mass loss of the mother dry particle as a result of collision according to the Eq. (1) would be small, smaller in fact than in the case of the raw particle. In order for the equation to be fulfilled in the case of comminution which takes place together with the combustion char process, the value of the fracture toughness rate should significantly decrease its value. On the basis of the obtained values, it may be acknowledged that this is the case in reality. The mean value of the fracture toughness rate after combustion of the volatile matter

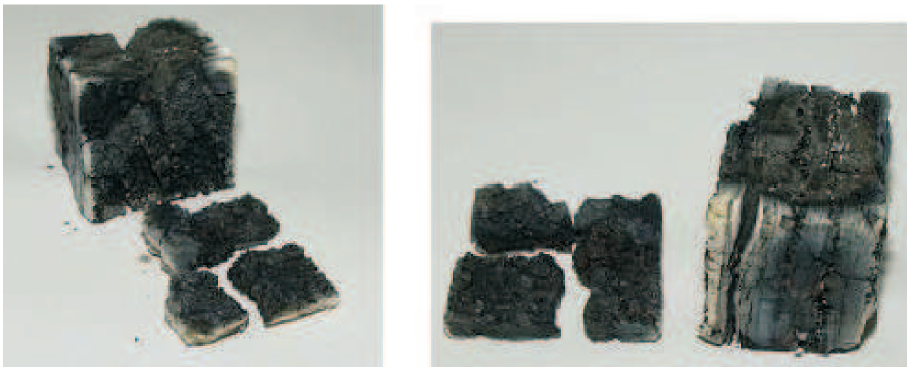

Figure 5. Delamination and fragmentation of a coal particle during its char combustion.

is one order of magnitude smaller than $K_c = 0.05381 \times 10^6$ Nm$^{-3/2}$ with relation to its value for coal without moisture $K_c = 0.4490 \times 10^6$ Nm$^{-3/2}$. The changes in the parameters of mechanical strength analysed previously observed suggest that we can expect only a further insignificant decrease in the value of the fracture toughness rate, which in turn will lead to the decreasing of the level of brittleness and consequently, to increasing its mass loss in the erosion process in conditions of the fluidized bed.

Figure 6. Combustion of volatile matter and char particles during tests on the fracture toughness rate.

4 Conclusions

The results obtained during the tests presented clearly point towards change in all the accepted strength parameters of coal used in the analysis, i.e.: static compression strength, Vickers hardness and fracture toughness. They indicate beyond all doubt the weakness of the coal structure both inside its volume, as well as on its surface. In all the phases of coal particles as a result of the complex physical chemical processes there are different strength parameters characterized. The most visible change may be observed after the volatile matter burns out at the moment of the initiation of char combustion. Thus, the key phenomenon causing the weakness of the coal structure seems to be the process of internal and first and foremost, external char combustion. The test methodology accepted for the practice of determining the strength parameters is correct, although it did not manage to directly determine all the values of the accepted range for char combustion. The results presented correlate with the processes of coal comminution very well as described by other authors during combustion in conditions of a circulating fluidized bed and explain the sudden change of susceptibility to the erosion process for pure mechanical attrition with and without assisted combustion. They can be used as parameters rendering the modelling of the mass loss of coal particle possible in conditions of a circulating fluidized bed that are difficult to describe.

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Zmiana własności mechanicznych węgla w kolejnych etapach procesu spalania

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

W badaniach podjęto próbę opisania zmian mechanicznej wytrzymałości ziaren węgli, która zachodzi podczas procesu ich spalania. Zmiany te mają bowiem podstawowe znaczenie w zachodzącym w komorze paleniskowej jednocześnie ze spalaniem procesie rozdrabniania węgla. Rozdrabnianie ma szczególne znaczenie podczas spalania w warunkach warstwy fluidalnej, gdzie w opinii wielu autorów jest jednym ze źródeł generowania straty niecałkowitego spalania. Analizy zmian mechanicznej wytrzymałości dokonano na podstawie trzech parametrów, tj. statycznej próby ściskania, twardości Vickersa oraz odporności na pękanie. Do badań wybrano węgiel energetyczny typu 31.2 z kopalni Sobieski powszechnie stosowany zarówno w paleniskach pyłowych jak i fluidyzacyjnych. Badania prowadzono na spreparowanych sześciennych ziarnach o wymiarach 15 x 15 mm. Analizę przeprowadzono dla węgla surowego oraz we wszystkich fazach jego spalania, tj. w procesie nagrzewania po wydzieleniu wilgoci, po wypaleniu części lotnych oraz w trakcie spalania karbonizatu. Uzyskane wyniki jednoznacznie wskazują na osłabianie struktury węgla wraz z przebiegającym procesem spalania. Zauważono największe osłabienie struktury po wypaleniu części lotnych w momencie zapłonu karbonizatu. Otrzymane wartości twardości oraz odporności na pękanie mogą zostać wykorzystane do modelowania procesu ubytku masy ziarna w warunkach warstwy fluidalnej szczególnie w jej górnym rozrzedzonym obszarze.