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Full Length Article

Relationship between the tensile strength of irregularly shaped coal particles and various fuel properties

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ABSTRACT

To gain a better understanding of inner-stress-induced coal particle fragmentation during coal utilization processes, the tensile strength of small and irregularly shaped coal particles was investigated, using eleven kinds of coals in the size range of 0.8–6.3 mm. It was found that the tensile strength significantly depends on particle size. As the particle size increases, the tensile strength asymptotically decreases, and the correlation between them could be described by a power function, requiring only different parameters for different coals. In addition, the effects of various fuel properties on the tensile strength are discussed. Coals with medium volatile matter content show the highest tensile strength, and the tensile strength generally increases with rising ash content and decreasing porosity. Based on the obtained results, a simplified model for the approximation of the tensile strength is developed involving the particle size and different fuel properties. A correlation analysis has exhibited that the number of required fuel parameters can be reduced to only two independent ones. This makes the tensile strength of coal particles directly predictable from the proximate and ultimate analysis of coals. With the aid of this prediction model, a better description of conversion processes may be achieved.

1. Introduction

The primary fragmentation of coal particles is of practical interest for various thermo-chemical coal utilization processes [1–10]. For example, during fluidized-bed gasification or combustion, the fragmentation can accelerate the reaction rate due to the enlarged particle surface area, increasing the carbon loss caused by the entrainment of fly ash etc. [11,12]. The mechanism of particle fragmentation has been widely discussed before [4,13–15]. Senneca et al. [14] proposed a primary fragmentation model suggesting that many fine particles are produced from the outer region of a coal particle as a result of thermal stress, and that relatively large fragments are generated from the inner region due to the devolatilization-induced pressure. Dacombe et al. [15] suggested that the thermal stress in the form of tensile stress at the particle center makes the particle fragment into relatively larger sub-fragments, and the compressive stress at particle surface make the outer part fragment into more and smaller particles. In the case of both thermal-stress-induced and devolatilization-induced fragmentation, particle fragmentation occurs only when the accumulated inner stress exceeds the mechanical strength of the coal particles. Concerning the mechanical properties of coal, the compressive strength of coal particles is much larger than the tensile strength, and therefore the fragmentation is usually considered to be initiated by tensile failure [13,15].

In terms of the tensile strength determination, several methods have been applied previously, as summarized by Evans [16,17]:

1. Conventional tensile test by subjecting the samples to a uniform tensile pull,
2. Bending tests by applying a bending moment to the sample,
3. Indentation test by applying a pair of flat indenters to opposite faces of a square coal specimen,
4. Diametrical compression of a solid disk, normally referred to as an indirect tension test or Brazilian test [18–20].

However, the conventional means of determining tensile strength require the preparation of regularly shaped specimens. Real particle shapes have clearly varied from the ideal shapes assumed by the different previously mentioned testing methods for tensile strength (cf. for example Mathews et al. [21]). Only few data have been published concerning the tensile strength of mm-sized and irregularly shaped coal particles [15]. Particle fragmentation, which is strongly related to the tensile strength of the particles, is a key process during coal conversion. It will directly affect other aspects of the conversion processes, like the

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release and coalescence of ash particles later causing fouling etc. [22,23]. Thus, the physical and mechanical properties of the coal will determine the temperature that has to be reached during the conversion processes for fragmentation. A clear lack of knowledge in the literature about the tensile strength properties for the common irregularly shaped particles is addressed. In addition, only a few publications regarding the prediction of the fragmentation behavior of particles are available [22,24]. All predictions of mechanical properties should be based on a relation to any measureable properties of the fuel. In principle, relationships between tensile strength and various parameters, e.g. the coal type (coal rank, maceral composition etc.), the micro- and macrostructure (micro-defect, fractures, porous structure, macromolecular matrix, surface energy etc.), and the sample itself (particle size, shape, layering etc.), are discerned in the literature [16,25–34]. Those properties, like the micro- and macrostructure of the coal, require a high effort for sample preparation and analysis. However, a lack of knowledge is recognized in the relation of mechanical properties and basic fuel properties (e.g. from proximate and ultimate analysis), which can be fairly easily accessed.

The present paper reports the results of tensile strength determination for the common irregularly shaped coal particles, which can provide a valuable contribution to a better understanding of the technically relevant process of practical coal particle fragmentation. For this purpose, a simplified prediction model is derived interrelating the tensile strength with basic fuel properties and, in consequence, the particle fragmentation. Thus, the virtue of the simplified determination of the mechanical properties of a fuel is the key to an understanding and a potential prediction of its features during fuel conversion processes (combustion, gasification etc.).

2. Materials and methods

2.1. Materials

Eleven kinds of coals were selected for the tensile strength measurements, covering a wide range of coal ranks, from brown coal to anthracite. In order to investigate the influence of particle size on the tensile strength, coal samples were separated by sieving them into different size groups (0.8–1.0 mm, 1.0–2.0 mm, 2.0–3.15 mm and 3.15–6.3 mm). The different size classes of each coal sample were stored in sealed glass flasks prior to use. The results of the proximate and ultimate analysis of the coal samples (according to the standards DIN 51,718–51,720, 51,724, 51,732–51,734) are presented in Table 1.

2.2. Methods

2.2.1. Density and porosity determination methods

As important coal structure parameters, the density and porosity of the investigated coals were also determined. A mercury porosimeter, the Micromeritics AutoPore IV 9500, was employed to determine the apparent density of the samples and a helium pycnometer was used to determine their true density. The porosity and specific pore volume were then calculated according to the obtained values for the apparent and true density [35,36], as presented in Table 2.

Table 2
Density and porosity analysis ([1]apparent density, [2]true density, and [3] vol fraction porosity).

Coal	ρ_{app}[1] (g/cm^3)	ρ_{true}[2] (g/cm^3)	P_v[3] (vol.%)	Specific pore volume (cm^3/g)
Schleenhain	1.05	1.42	26.00	0.25
Schoeningen	0.95	1.44	34.00	0.36
Mongolia	1.26	1.41	10.92	0.09
Rudoltowy	1.29	1.32	2.75	0.02
Murcki	1.29	1.46	11.14	0.09
Sapropel	1.50	1.58	5.23	0.03
Mongolia MGB	1.28	1.32	3.62	0.03
Lazy	1.43	1.46	1.58	0.01
Sasol	1.48	1.60	7.04	0.05
Uong Bi	1.33	1.37	2.43	0.02
Ibbenbueren	1.38	1.44	4.08	0.03

2.2.2. Tensile strength determination methods

In the present work, relatively small and irregularly shaped specimens in the size range of 0.8–6.3 mm were used. It is not easy to prepare regularly shaped specimens for these particles. Apart from that, handling operations such as clamping or bending are also very difficult because of the coal specimens' small size and brittleness, and the preparation or operation processes themselves also inevitably influence the strength values, making tensile strength measurements for such particles a challenging task.

Based on a series of calculations and experimental verifications, Hiramatsu et al. [37] previously proposed a method to determine the tensile strength of irregularly shaped specimens using a compression test, a more convenient method.

Under compression, the tensile stress is generated inside particles perpendicular to the loading direction, whereupon at least one or two of the following phenomena could appear [37]:

1. Fracture along the loading axial direction due to the tensile stress,
2. Crushing caused by the compressive stress near the loading points,
3. Compression fracture over the whole range between the two loading points.

In our experiments performed on a uniaxial testing device, coal specimens usually undergo a clear fracture in the direction of the applied load, which splits the particles into two or three sub-fragments. A

Table 1
Proximate and ultimate analysis of coal samples ([1]dry and ash-free basis, [2]moisture content, air-dry basis, [3]ash content, dry basis, [4]volatile matter content, dry basis, and [5]fixed carbon, dry basis).

Coal	Type	Proximate analysis (wt%)				Ultimate analysis (wt%, daf[1])				
		M_{ad}[2]	A_d[3]	V_d[4]	$C_{d\text{-}fix}$[5]	C	H	N	S	O
Schleenhain	Brown coal	15.5	11.60	52.40	36.0	70.60	5.10	0.60	4.30	19.40
Schoeningen	Brown coal	12.57	11.55	51.82	36.62	70.80	5.54	0.40	7.52	15.75
Mongolia	Brown coal	12.72	12.69	38.99	48.32	76.30	5.31	1.55	0.48	16.36
Rudoltowy	High volatile bituminous	1.73	5.70	33.10	61.20	86.88	5.36	1.55	0.56	5.65
Murcki	High volatile bituminous	5.80	12.22	31.85	55.93	81.83	4.55	1.31	0.68	11.63
Sapropel	Subbituminous	2.55	34.41	30.14	35.45	80.85	5.67	1.91	0.69	10.89
Mongolia MGB	Medium volatile bituminous	0.73	9.67	28.40	61.93	88.35	5.47	2.06	0.79	3.33
Lazy	High volatile bituminous	1.32	23.48	24.96	51.56	87.35	4.94	1.42	0.42	5.87
Sasol	Medium volatile bituminous	6.04	25.33	23.29	51.38	79.58	4.06	2.06	0.29	14.00
Uong Bi	Anthracite	0.95	1.10	7.55	91.35	93.83	3.66	1.37	0.08	1.06
Ibbenbueren	Anthracite	2.89	10.66	6.54	82.80	94.13	3.16	1.21	0.85	0.65