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Mechanical Strength of Extrusion Briquettes (BREX) for Blast-Furnace and Ferroalloy Production: II. Effect of the Method of Grinding Coke Breeze on the Strength of Extrusion Briquettes

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Abstract—The influence of the method of grinding coke breeze on the strength and the behavior of extrusion briquette (BREX) during static loading is studied. It is found that the size, the shape, and the surface relief of coke breeze particles affect the character of BREX fracture. The application of a shearing extruder for preliminary refinement of coke breeze can result in viscoelastic fracture of BREX due to an increase in its impact toughness.

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INTRODUCTION

Coke is used as a reducing agent to manufacture cast iron and ferroalloys in blast furnaces and electric ore smelting furnaces. To ensure normal melting conditions, the coke lump size must be larger than 20–25 mm in a blast furnace and larger than 5–10 mm in an electric ore smelting furnace. Smaller fractions of coke are sifted out when a charge is prepared for melting. Small fractions of coke can be returned to the process of production by their agglomeration after specific preparation.

The practice of agglomeration of disperse and anthropogenic materials by briquetting has received wide acceptance in metallurgy. Stiff vacuum extrusion, which is a highly productive and efficient technology of agglomeration of the natural and anthropogenic materials used in metallurgy, is rapidly growing. The specific features of this briquetting technology, which provoked deep interest to it in almost all ferrous metallurgy industries, were described in our works [1–3].

In some cases, the granulometric composition of the initial material should be changed (milling, fragmentation) for the charge to be briquetted to acquire the plasticity required for extrusion. The method of such a treatment can strongly affect the strength of an extrusion briquette (BREX), its reaction to a mechanical action in the form of static or impact loads, and the character of fracture. For the practice of briquetting, it is important to understand the relation between the granulometric composition of BREX material particles and their geometry. This is illustrated by the results of our study of the method of charge grinding on the strength of BREX of the same composition. We studied the same batch of raw materials (coke breeze) but used different methods of grinding.

EXPERIMENTAL

To investigate the effect of the method of grinding a material, i.e., a change in its granulometric composition, on the strength of BREX with a cement–bentonite binder, we compared the properties of BREX made of coke breeze preliminarily ground by the following three methods: in a hammer mill, in a roll crusher, and by double extrusion through a shearing plate in an extruder (Fig. 1). To analyze the granulometric composition of the ground material, we used wet screening in sizing screens with a screen size of 4.75–0.045 mm. The moisture content was determined with a humidity analyzer. To analyze the sample density, we applied a calibrated electronic balance that could measure the density.

The results of granulometric analysis of coke breeze before and after grinding treatment are presented in Table 1 and Fig. 2. It is seen that the degree of grinding of coke breeze is maximal after double extrusion through a shearing plate in an extruder. The effect of deep grinding in this case is reached due to the application of high shear stresses. The use of a hammer mill for such a material was found to be ineffective, and the

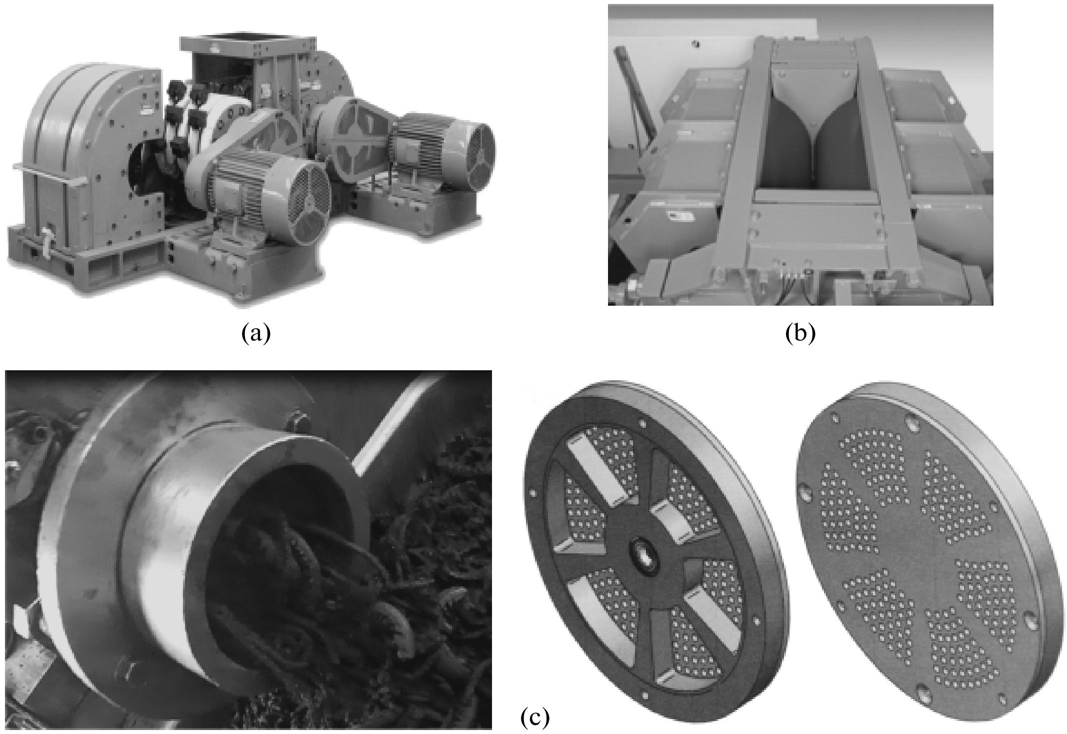

Fig. 1. Equipment and means for grinding the materials intended for stiff extrusion: (a) Steele hammer mill, (b) Steele roll crusher, and (c) extrusion through a shearing plate in an extruder (on the right).

granulometric composition of the ground material differed weakly from that of the initial coke breeze.

A laboratory Hobart mixer was used for mixing with water and screwing a ground material, and it modeled charge treatment in the open volume of a clay mill with a gate valve. The laboratory extruder used to fabricate BREX samples imitated the extrusion of a material through degasser grids into a vacuum chamber and, then, extrusion. All BREX samples had the same composition, namely, 94% coke breeze, 5% Portland cement, and 1% bentonite.

RESULTS AND DISCUSSION

According to the method of BREX grinding, the following numbers were assigned to ground BREX samples: sample 1, coke breeze ground in a roll crusher; sample 2, coke breeze subjected to double extrusion by an extruder auger through a shearing plate (3 mm thick) with numerous holes (extruding auger placed near this plate rotates and extrude the material through these holes, and the material is fragmented due to grinding); and sample 3, coke breeze ground in a hammer mill. Table 2 gives the extrusion parameters

Table 1. Granulometric composition of coke breeze for various versions of treatment for additional grinding

Set of sieves		Yield (%) of neighboring classes of coke breeze			
mesh	mm	initial material	hammer mill	roll crusher	double extrusion
4	4.75	97	100	100	100
8	2.36	78	83	96	98
16	1.16	53	63	75	95
30	0.6	37	44	58	91
50	0.3	25	29	41	76
100	0.15	18	20	29	54
200	0.075	13	14	20	38
325	0.045	11	10	16	30

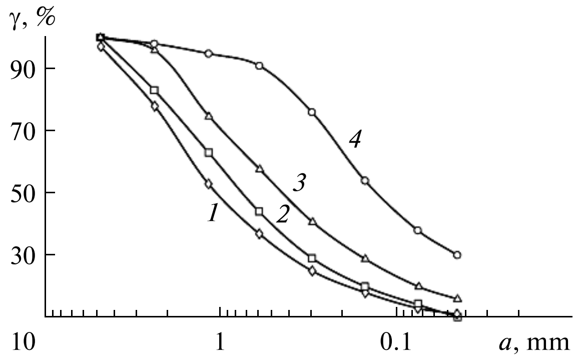

Fig. 2. Granulometric composition of coke breeze in the following states: (*1*) initial and (*2–4*) after additional grinding in a hammer mill, in a roll crusher, and double extrusion in an extruder, respectively. The points at the curves correspond to the sieves from a set (see Table 1). γ is the yield of the oversize mass, and *a* is the mesh size.

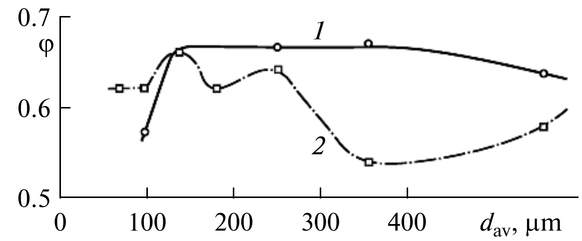

Fig. 3. Particle shape factor φ vs. the average particle size upon grinding in (*1*) hammer mill and (*2*) roll crusher.

and the physical properties of the BREX samples. As is seen from these data, the extrusion of the first two mixtures was carried out at similar process parameters, and the extrusion of coarser mixture 3 particles (hammer mill) is accompanied by an increase in the material temperature. As a result, the BREX made of the largest particles turned out to have the minimum strength during axial compression tests. As for energy consumption, the extrusion of mixture no. 1 was most efficient. Its excellent extrusion ability can be related to the material particle shape after grinding in a roll crusher, which favors the plane-parallel orientation of particles.

The difference between the tensile strengths of samples 1 and 2 is insignificant and can only indicate an earlier beginning of cracking in BREX 2. It also follows from these data that the density of the BREX after double extrusion is higher than those of the BREX samples made of ground and milled coke breeze by 2.5%. Obviously, the dense packing of BREX 2 particles results from a high degree of material grinding. In contrast to BREX samples 1 and 3, no dewatering of the mixture during extrusion was detected in this case.

The difference between the compressive strengths of the BREX samples prepared from coke breeze of the same batch but differently treated can be caused by a number of factors related to different particle sizes and shapes and a particle surface relief. The particle shape after grinding can depend on the material characteristics and the method of grinding, including its time [4–6]. For example, it is generally accepted that the material after grinding in roll crushers mainly consists of angular particles, whereas the material particles after ball and hammer mills usually have the same size and a rounded shape. Grinding in roll crushers occurs under the action of compressive, shear, and rubbing forces. As a result, rough particles having sharp projections, many edges and corners, and (correspondingly) a large contact surface form. The particle surfaces after hammer mills are polished due to impact actions, and particles acquire a rounded shape.

For example, the authors of [7] studied the effect of the type of a grinding device on the particle shape of oil coke of the following two types: low-porosity coke with thick cell walls without visible cracks and fissured coke, the porosity and the cell wall thickness of which were distributed over a wide range. For the coke of the first type, the method of grinding did not affect the shape of particles 200–600 μm in size. For the porous and fissured coke, different dependences of the particle shape on the particle size were revealed for grinding in a hammer mill and in a roll crusher (Fig. 3) [7]. These curves reflect the following dependence of the shape factor: $\varphi = 1.1V^{1/3}N^{1/6}A^{-1/2}$, where V is the specific particle volume (cm^3/g), N is the number of particles in 1 g substance, and A is the specific surface area (cm^2/g). The material particles ground in a hammer mill are characterized by stable high shape factors, which indicates the closeness of the shapes of most particles to a rounded shape in the size range under study. For the particles of the material ground in a roll crusher, the shape factors in the particle size range 140–600 μm are lower and minimal at a size of ~350 μm,

Table 2. Extrusion parameters and the physical properties of BREX made of coke breeze

BREX sample (grinding method)	W, %	p, kPa	t, °C	ρ, g/cm^3	σ, MPa
No. 1 (roll crusher)	16.5	2.03	30.56	1.630	3.7
No. 2 (double extrusion)	16.7	2.37	33.33	1.674	3.4
No. 3 (hammer mill)	16.6	10.81	55.56	1.627	2.0

W is the humidity, p is the vacuum, t is the material temperature, ρ is the BREX density, and σ is the compressive strength of BREX.

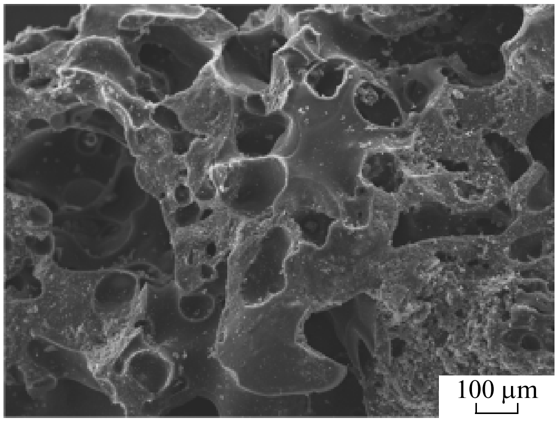

Fig. 4. Microstructure of coke breeze particles (SEM).

which supports the conclusion about a more nonuniform particle shape after grinding in a roll crusher.

As in [7], we used a porous and fissured material. Figure 4 shows an image of coke breeze particles taken with a JEOL JSM-6490 LV scanning electron microscope (SEM). In Fig. 5, we compare the particle shapes of the initial coke breeze and the coke breeze after additional grinding. The initial coke breeze particles are characterized by hillocks (rounded projections), which are typical of coke; they belong to internal (not opened) pores located under the upper layers of the carbon material. It is seen that the particles after a roll crusher and double extrusion through an extruder have a nonuniform angular shape, whereas the coke breeze particles ground in a hammer mill have a rounded shape.

The BREX samples were subjected to tensile splitting tests on a bench-type one-column electromechanical Instron 3345 tensile-testing machine at a load of 5 kN. When studying the statistics of BREX orientation distribution in a charge, we [8, 9] found that this external load is most probable for a cylindrical BREX. Figure 6 shows the results of testing specially prepared cylindrical specimens of BREX 1–3 25 mm in diameter and 20 mm in height. It is seen that, at an approximately the same carrying ability of the BREX specimens, their reactions to an applied load are different.

The difference in the maximum loads can be related to defects in the specimens. However, the dif-

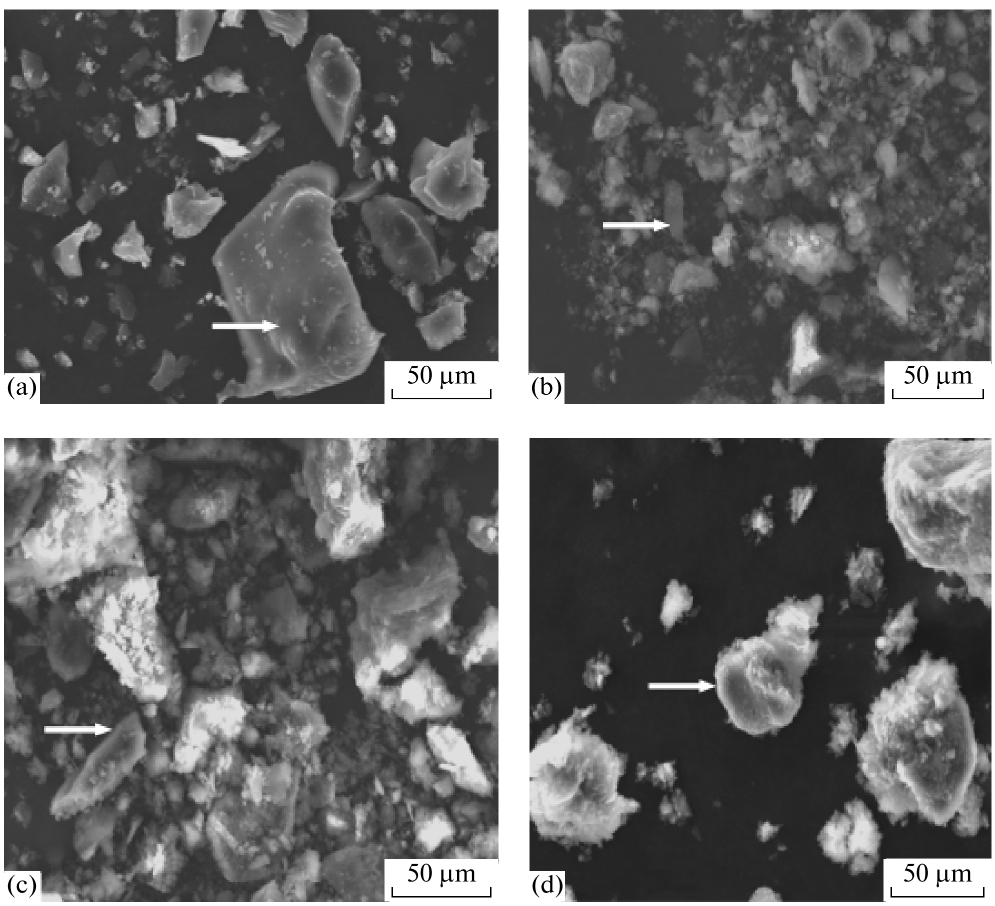

Fig. 5. Micrographs of (a) initial coke breeze particles and after additional grinding (b) in roll crusher, (c) by double extrusion through an extruder, and (d) in a hammer mill.

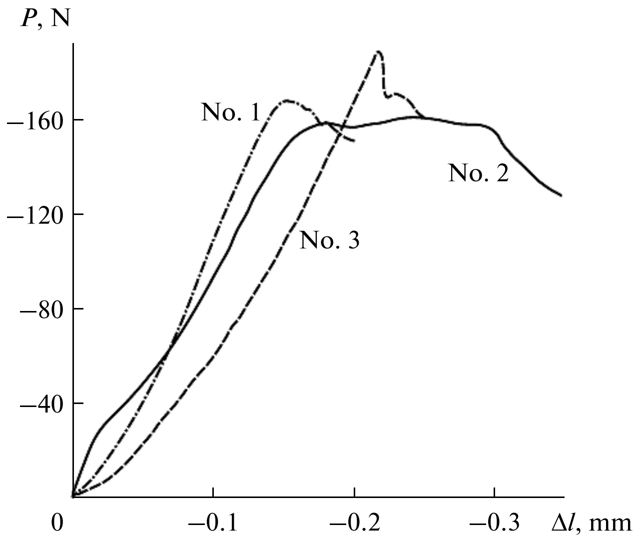

Fig. 6. Load *P*–displacement Δ*l* curves for cleavage tensile tests of BREX.

ference in the characters of behavior can have radically different causes. BREX 2 demonstrates ductile fracture, which is indicated by the existence of a yield plateau, i.e., the horizontal component of the curve of BREX 2. This phenomenon is thought to be explained by a "relay-race" transfer of gliding from grain to grain in terms of the Hall–Petch relation [10]. In this case, a grain boundary is a barrier to dislocation motion, which causes dislocation nucleation and development in a neighboring grain. In other words, the larger the number of barriers to be overcome, the lower the dislocation motion dynamics and the higher the crack development resistance.

Apparently, there exists a threshold particle size, below which cracks cannot propagate in BREX. Obviously, the granulometric composition of the BREX 2 mixture favors this scenario due to the highest content of thin particles among the other mixtures (see Table 2). The integrity of BREX 2 is retained even after tests; therefore, a high impact toughness can be expected in it. At this type of loading, local fracture zones will not cause full fracture of a specimen and debris formation. The load–displacement curves of BREX 1 and 3 decrease significantly after crack initiation, which points to more brittle fracture of these specimens. The brittle fracture in BREX 1 develops more slowly than in BREX 3 because of a smaller average particle size. Note that these circumstances are very important for the practice of briquetting. Several stages of charging–discharging related to throwing down briquettes can be required to supply the briquettes to a furnace even in one enterprise. When the impact toughness of an agglomerated product is increased, the logistics of its supply to the site of using, including a far site, can be significantly simplified and, hence, become cheaper. It is important for the practice of stiff extrusion that a change in the behavior of BREX under an external mechanical action was achieved using the equipment used for agglomeration.

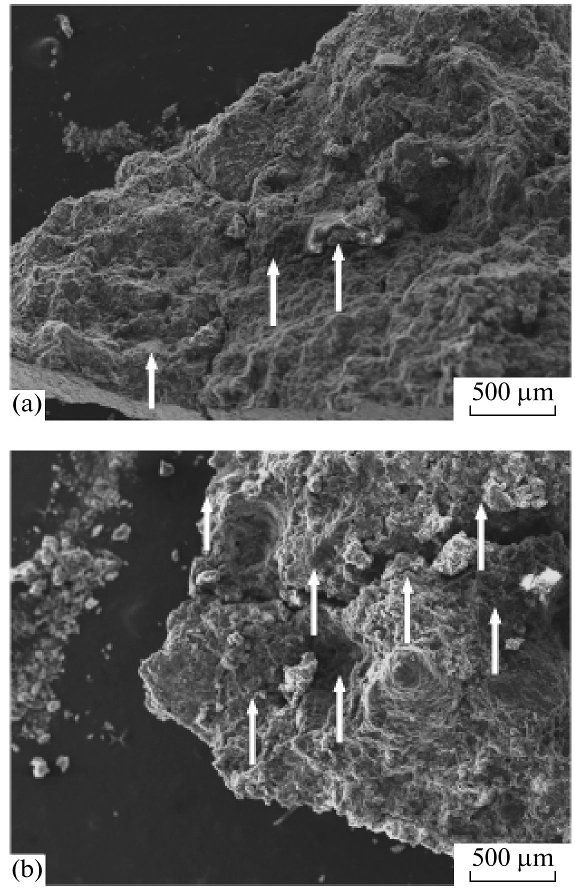

Fig. 7. SEM micrographs of the particle surfaces in BREX (a) 3 and (b) 2.

In addition to the operation of the physical mechanisms that weaken dislocation propagation, which lead to a high strength of BREX made of small particles, the distribution of a binder in the BREX body also substantially contributes to the strength of BREX. It is clear that the low strength of BREX 3 during compression can be explained by a small number of contacts between particles. For illustration, Fig. 7 shows micrographs of the particle surfaces in BREX 3 (grinding in a hammer mill) and BREX 2 (double extrusion through a shearing plate). It is clearly visible that, because of lower particle surface roughness of BREX 3 as compared to BREX 2, the number of hillocks with a binder (cement and bentonite) on their surface (bright aggregates) is significantly smaller. (Since minerals contain heavy chemical elements, they manifest themselves as bright precipitates in micrographs.) Therefore, the surface relief of the BREX 2 particles favors good adhesion of particles also due to the large binder volume that covers the sites of particle–particle contacts.

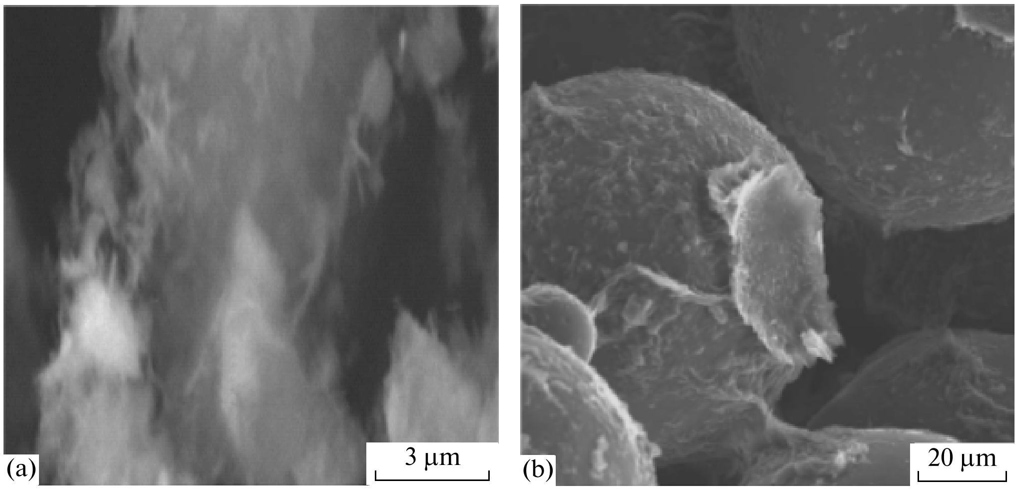

Fig. 8. Bentonite fibers on (a) the particle surface in BREX 2 and (b) on the surface of glass microspheres [11].

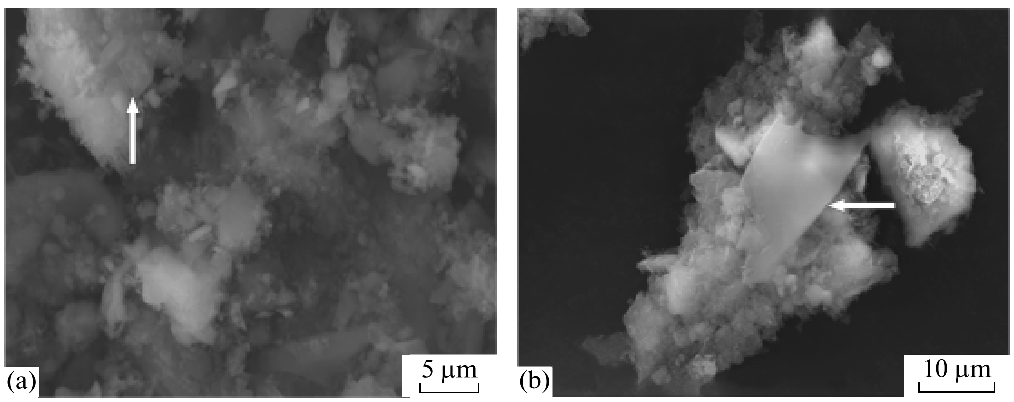

Fig. 9. Bentonite particles in BREX (a) 1 and (b) 3.

When studying the particle surfaces of BREX 2, we detected bentonite fibers, which were described for the first time in [11], on it. Figure 8 shows the surface of BREX 2 particle and the surfaces of glass microspheres subjected to soft rolling (without crashing) in a roll crusher, which imitated shear stresses. This treatment promoted the development of bentonite fibers covering the particle surface. After this preliminary treatment of a mixture of magnetite concentrate and bentonite, the fraction of bentonite required for the given strength decreased twofold (from 0.66 to 0.33% concentrate mass). The appearance of this structure in BREX 2 is likely to result from the shear stress applied to the material during auger extrusion. The effect of appearance of bentonite fibers is less pronounced in BREX 1 and 3, which is likely to be associated with a lower fraction of thin particles. This phenomenon will be studied later. BREX 1 and 3 have predominantly lamellar and flakelike bentonite particles (Fig. 9).

CONCLUSIONS

(1) The method of grinding coke breeze can influence the size, shape, and surface relief of particles. The degree of influence depends on the structure of the material, mainly its porosity. A nonuniform surface relief of coke breeze particles (surface roughness) favors an increase in the BREX strength due to an increase in the number of contact sites and the binder concentration near these sites.

(2) The granulometric composition of coke breeze affects both the compressive strength and the character of BREX fracture during static and dynamic loading. Depending on the degree of grinding, brittle fracture can change in to viscoelastic fracture, which leads to an increase in the impact toughness of BREX.

(3) The shear stresses that accompany extrusion can promote the formation of a fibrous structure of bentonite, which increases the strength of BREX. A shearing extruder can be used to achieve the required degree of refinement of coke breeze.

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