CRUMBLING CRITERIA FOR WET IRON-ORE PELLETS DRIED BY THE LAMINAR CONVECTION PROCESS

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The paper presents a study of the changes in the Posnov and Kirpichev numbers and of crack formation during the intensive laminar convective drying of iron-ore pellets. A relation is established between the criterion of crack formation and the hydrophysical properties of a nodulized sample.

The mechanical strength of individual iron-ore pellets generally increases while they are dried under laboratory conditions. During laminar convective drying under more severe industrial conditions, however, the pellet structure breaks down, on the one hand, causing an irreversible reduction of mechanical strength in the final product and, on the other hand, disturbing the thermal and hydrodynamic operating mode of the calcination equipment.

Thermal crumbling of pellets is caused by the development of volume stresses which exceed the structural–mechanical strength as well as by the higher than nominal humidity and temperature gradients.

It is the operating parameters of the drying process which largely determine the trend of changes in the structural–mechanical properties of pellets.

When iron-ore pellets are dried by laminar convection very intensively, there appear on the conveyor belt of the drying–calcinating apparatus two phenomena related to the thermal crumbling of their structure: crack formation and "shock" crushing. Crack formation is evidence of a local surface breakdown which occurs during the initial drying period, when the temperature of the heating gas is relatively low and the moisture content in the pellets is still quite high. "Shock" crushing is a full-scale explosive high-temperature breakdown of pellets which occurs during the final period of drying, when the residual moisture content is low. The fines produced in this process fill up the interstitial space between pellets and sharply reduce the gas permeability of the layer.

According to the Lykov theory, K_T, the basic indicator of the thermal stability of capillary-porous bodies during drying, is defined in terms of the Kirpichev number Ki and the Posnov number Pn [1]:

$$K_T = \frac{2}{3}\left[\frac{1}{3}\,\mathrm{Ki} + \frac{(t_s - t_c)}{T_m}\,\mathrm{Pn}\right]. \tag{1}$$

In our case the Kirpichev number will be calculated from the relation

$$\mathrm{Ki} = 2\left(\frac{U_c - U_s}{\bar{U}_0}\right). \tag{2}$$

The Posnov number is defined by the expression

$$\mathrm{Pn} = \frac{\delta \Delta t}{\Delta U}. \tag{3}$$

For the initial period of drying, while the capillary moisture is removed, the temperature gradient remains negligibly small and the crack formation criterion can in this case be determined from the Kirpichev number alone:

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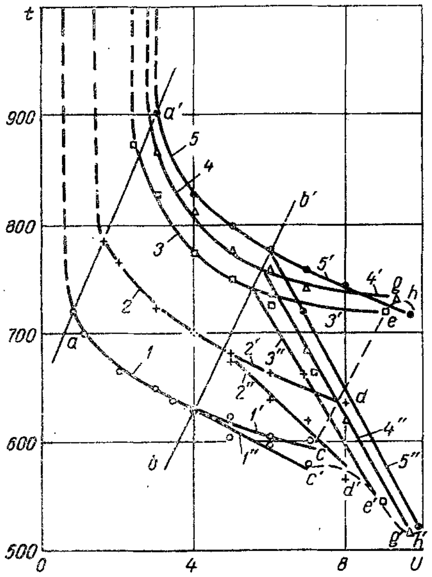

Fig. 1. Effect of initial moisture content in pellets (%) on their thermal stability (°C): 1) 100% concentrate with K = 0.55; 2) 92% concentrate + 8% limestone with K = 0.62; 3) 91% concentrate + 8% limestone + 1% bentonite with K = 0.68; 4) 97% concentrate + 3% bentonite with K = 0.72; 5) 95% concentrate + 5% bentonite with K = 0.78. Lines 1', 2', 3', 4', and 5' refer to the "shock" crushing temperature. Lines 1", 2", 3", 4", and 5" refer to the crack formation temperature.

$$K_T = \frac{1}{3} Ki. \tag{4}$$

The final period of laminar convection drying is characterized by the appearance of large temperature gradients. A sharp rise in the temperature of the heat-carrying gas at the boundary between the heating zone and the drying zone of the apparatus results in a step increase in the temperature gradient accompanied, as a rule, by "shock" crushing. The crack formation criterion is in this case determined essentially by the Posnov number:

$$K_T = \frac{2}{3} \frac{(t_s - t_c)}{T_m} Pn. \tag{5}$$

Wet iron-ore pellets belong to a class of materials intermediate between those that are properly capillary-porous ones and those colloidally capillary-porous.

A considerable effect on the thermal stability of such materials during drying is exerted by their natural properties, the forces, and the character of their interaction with water.

In the case of a capillary-porous material it is convenient to evaluate the entire complex of hydrophysical properties in terms of the nodularity factor K [2]:

$$K = \frac{W_{MMM}}{W_{MCM} - W_{MMM}}, \tag{6}$$

where W_{MMM} is the maximum molecular moisture content (%), which expresses the energy relation in the nodular system, and W_{MCM} is the maximum capillary moisture content (%), which represents a structural parameter.

The A. F. Lebedev method refined by A. V. Vasil'ev was used for determining W_{MMM}. This method consists in the removal of capillary water from the specimens of a tested material by means of a suction medium at a pressure of 75 kgf/cm^2. The method of capillary saturation of core specimens was used for determining W_{MCM}.

The practical determination of the Kirpichev and Posnov numbers involves setting up special and rather cumbersome experiments. For this reason, it was deemed worthwhile to establish a relation between K_T and K, since the latter had to be determined anyway for the proper choice of ore samples and of pelletizing process conditions. The establishment of such a relation would permit the prediction of thermal stability of pellets.

For our study we used specimens of nodulized material taken from production samples of highly enriched 0.1-0 mm grain-size magnetite concentrate, 0.15-0 mm grain-size limestone, and 0.1-0 mm grain-size bentonite at the nodulizing plant of the Sokolovsk–Sarbaisk mining and processing combine, as well as specimens of fine-grain magnetite sludge from the Kemenovsk aniline-dye plant and quartz sand. The pellets were prepared both from individual components and from various mixtures of the named ingredients.

The wet material was nodulized on a dish-type granulator 1 m in diameter. The 15 ± 1 mm fraction of pellets was used for the tests.

The thermal stability of pellets was determined quantitatively on the basis of the initial crack formation and "shock" crushing temperatures. For this purpose, batches of pellets were placed in a muffle furnace and heated up to a definite constant temperature at which they were then held for 7 min. After that, the pellets were examined under an ×8 magnifying glass, to check whether surface cracks had formed. The furnace temperature was then raised further in 20°C steps until crack formation and "shock" crushing occurred. A fresh batch of pellets was used for each of these subsequent higher-temperature tests.

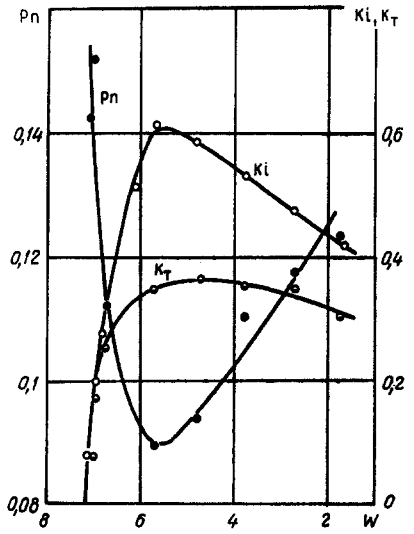

Fig. 2

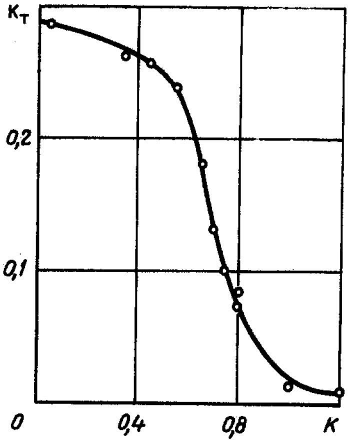

Fig. 3

Fig. 2. Values of Pn, Ki, and K_T as functions of the average moisture content in pellets (%).

Fig. 3. Effect of the nodularity factor K for an ore sample on the crack formation criterion K_T.

To determine the moisture and temperature gradients during drying, a batch of freshly-prepared pellets was placed in the muffle furnace at the initial crack formation temperature, which had been determined previously for each material and ore sample. For measuring the temperatures at the surface and at the center of pellets we used Chromel–Alumel thermocouples connected to a multipoint EPP-09 potentiometer. Samples were tested for moisture content every 30 sec. To determine the surface moisture content we removed a 1 mm thick surface layer from the pellet. With a special template, a 3 mm^3 cube was cut from the center of a pellet in order to test the internal moisture content. Depending on the variance of test values, the number of repeated measurements ranged from 30 to 40.

The results of the experiment are presented graphically in Figs. 1-3.

In Fig. 1 the effect of moisture content on the thermal stability of pellets is shown; to evaluate this effect the specimens were subjected to optimal nodulizing conditions followed by drying at a 105°C temperature until definite residual moisture content levels were reached and then testing for thermal stability was conducted; in addition, the temperatures of initial crack formation and "shock" crushing were measured.

It is noteworthy that the pellets from various ore samples become resistant to crack formation and "shock" crushing at specific residual moisture content levels. These moisture content levels (points on the nominal line *aa'*) correspond to the hydrophysical constant of the nodulized materials, namely to the maximum hygroscopic moisture capacity (W_{MHM}) determined by the standard method [1].

As the moisture content becomes higher, the degree of structural breakdown in the pellets increases and it begins at a lower temperature. When the residual moisture content remains between the values of W_{MHM} and W_{MMM} (points on line bb'), one observes only one mode of breakdown ("shock" crushing).

As capillary water appears in the pellet structure, i.e., as the residual moisture content level exceeds W_{MMM}, crack formation and "shock" crushing begin at different temperature levels. The higher the content of capillary moisture, the greater will be the temperature difference between the beginning of crack formation and the beginning of "shock" crushing. The greatest temperature difference between the beginnings of both breakdown modes in pellets corresponds to a moisture content equal to the optimum moisture content for nodulizing (on the lines points c', d', e', g', and h' denote the beginning of crack formation, points c, d, e, g, and h correspond to the beginning of "shock" crushing).

The data in Fig. 2 relate to the kinetics of changes in the Pn, Ki, and K_T numbers which occur during the drying of pellets sampled from industrial-grade raw material: 91% magnetite concentrate + 8% limestone + 1% bentonite.

As moisture is removed from the pellets, the values of Ki and K_T increase until they reach their maxima at a residual moisture content of about 5.5%. The Posnov number, on the contrary, first decreases and then increases.

This indicates that at the start of the drying process the thermal stability of pellets is largely determined by the temperature gradient. The effect of the temperature gradient then diminishes rapidly, while the Kirpichev number becomes the determining and increasingly important factor. The bending curves of the Ki, K_T, and Pn against W can evidently be explained as follows. At a moisture content of about 5.5% (corresponding to the value of W_{MMM}) there begins a rapid deepening of the evaporation zone. The temperature gradient between the dehydrated surfaces and the pellet centers increases rapidly, causing the sharp increase of the Pn number. The moisture gradient at the start of the drying process increases rapidly, since the surface of a pellet becomes dehydrated while the center has not yet heated up and still retains its moisture. The poor thermal conductivity of moisture aggravates the situation. As heat penetrates deeper into a pellet, vapor forms within the entire volume and, as a result of the pressure gradient, the moisture moves rapidly to the surface so that the distribution of moisture content becomes more uniform, i. e., the moisture gradient decreases and with it the Ki number.

The initial period of drying is characterized by an almost linear relation between the Ki number and the moisture content in the surface layer. This empirical relation can be expressed approximately as follows:

$$Ki = 3{,}5 - 0{,}472W. \tag{7}$$

The relation between the nodularity factor K and the crack formation criterion K_T is shown in Fig. 3. The curve has been fitted on the Promin' computer by the method of least squares. The resulting equation is

$$K_т = 0{,}527 \exp(-2{,}6K^4). \tag{8}$$

Equations (7) and (8) are valid for assessing the thermal stability of capillary-porous bodies with a moisture content between W_{MMM} and W_{MCM}.

The nondularity factor K for nodulizable materials lies between 0.5 and 0.8; the relation between K_T and K may be considered approximately linear and may be expressed by the simpler equation:

$$K_т = 1{,}15 - 1{,}21K. \tag{9}$$

Under practical conditions, a directed change in the thermal stability of nodulized material can be effected by regulating the hydrophysical properties of the nodulized batch; this is achieved by varying the quality and the quantity of added bentonite, of various surface-active substances and structure-shaping additives, by varying the pH of suspensions in the pores, etc.

The authors express their sincere appreciation to Academician A. V. Lykov for his valuable comments and for defining the objectives of this study.

NOTATION

t_s	is the temperature at the pellet surface, °C;
t_c	is the temperature at the pellet center, °C;
T_m	is the temperature of the drying medium, °K;
U_c	is the moisture content in the pellet center, %;
U_s	is the moisture content at the pellet surface, %;
U_0	is the initial average moisture content in the pellets, %;
δ	is the thermal-gradient coefficient $(°C)^{-1}$;
Δt	is the temperature gradient, °C/m;
ΔU	is the moisture gradient, %/m;
t	is the temperature, °C;
U	is the moisture content in the pellets, %.

LITERATURE CITED

1. A. V. Lykov, Theory of Drying [in Russian], Énergiya (1968).
2. V. M. Vityugin and A. S. Bogma, Izv. VUZ. Chernaya Metallurgiya, No. 4 (1969).