

Resource-energy-saving technologies and equipment for complex processing of man-made materials

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Abstract: Using the fundamental kinetic laws of materials grinding processes, a resource-energy-saving technology for complex processing and mechanoactivation of mineral components has been developed. For the technology, patent-protected energy-efficient grinding units for selective grinding of materials have been developed: press-roll grinders (PRG) for volume-shear deformation (VSD) of materials and obtaining their microdefect structure; drum ball mills (DBMs) with internal energy-exchanging devices (IEDs), which implement impact-crushing-abrading action with less 10–20 % grinding load. A technological complex was developed for mechanoactivation of fine-grained materials and obtain nanostructured composite mixtures from them: "PRG–VSD" – vibration-centrifugal unit (VCU) of selective grinding at each stage – vortex-acoustic dispersants (VADs) for obtaining ultrafine particles < 5 μm with mechanical-aerodynamic and acoustic grinding. Resource-energy-saving technology has been tested for complex thermomechanical processing of quartzite-iron-containing waste at the Lebedinsky mining and processing plant for production of pigments-fillers for the purpose of volumetric dyeing of products.

Keywords: resource-energy-saving technology; step-by-step selective grinding; energy-saving grinding units; quartzite-iron-containing wastes; pigments.

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Ресурсоэнергосберегающие технологии и технические средства для комплексной переработки техногенных материалов

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Аннотация: С использованием основополагающих кинетических закономерностей процессов измельчения материалов разработана ресурсоэнергосберегающая технология комплексной переработки и механоактивации минеральных компонентов. Для технологии разработаны патентно-защищенные энергоэффективные помольные агрегаты селективного измельчения материалов: пресс-валковые измельчители (ПВИ) – для объемно-сдвигового деформирования (ОСД) материалов и получения их микродефектной структуры; барабанные шаровые мельницы (БШМ) с внутренними энергообменными устройствами (ВЭУ), реализующие ударно-раздавливающе-истирающее воздействие при меньшей на 10...20 % мелющей загрузке. Для механоактивации мелкозернистых материалов и получения из них наноструктурированных композиционных смесей разработан технологический комплекс:

«ПВИ-ОСД – вибро-центробежный агрегат (ВЦА) селективного измельчения на каждой стадии – вихре-акустические диспергаторы (ВАД) для получения ультрадисперсных частиц < 5 мкм при механо-аэродинамическом и акустическом воздействии измельчающей среды. Ресурсоэнергосберегающая технология апробирована при комплексной механотермической переработке кварцит-железосодержащих отходов обогатительного предприятия Лебединский ГОКа для получения пигментов-наполнителей в целях объемного окрашивания изделий.

Ключевые слова: ресурсоэнергосберегающая технология; постадийное селективное измельчение; энергосберегающие помольные агрегаты; кварцит-железосодержащие отходы; пигменты.

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1. Introduction

At the present stage of industrial production development in industrialized countries, one of the most important tasks is integrated processing of man-made materials using innovative technologies. At the same time, resource-energy-saving technologies for obtaining finely dispersed materials with nanostructured components are of great importance.

About 2.01 billion tons of waste are generated annually in the world (2016 data), and about 61 million in the Russian Federation, of which only 4–5 % are involved in processing [1 – 6]. The largest amount of waste is produced by industrial enterprises, primarily ore mining and ore dressing. At Lebedinsky mining and processing plant (Lebedinsky MPP), the tailings storage facility is one of the largest in Russia – the land drainage is 1529 hectares, which exceeds the areas allocated for the quarry (1100 hectares). The annual volume of stored waste is 18.5 million m³.

Particular importance is the process of processing waste – grinding silica-containing man-made materials (ferruginous quartzite, magnetic separation waste, quartzite sand, quartzite, basalt fiber waste, etc.) of various industries: mining, silicate, ceramic, refractory, heat-insulating materials, etc. [5 – 7]. At the same time, unused reserves contain technologies for selective grinding of materials at each stage of their processing. However, its successful implementation is largely hampered by the lack of special technical facilities that take into account physical and mechanical characteristics of the milled materials (initial particle size distribution; density and strength of particles, anisotropy of their texture, millability, etc.), and processing conditions.

The theoretical and experimental research conducted by the authors, design and technological developments, their experimental and industrial testing made it possible to implement the results in practice – to reduce the energy consumption for grinding to 20 – 30 % [8].

The implementation of selective grinding of materials was carried out step by step: for large-scale production – in the technological complex – “Press-roll grinder” (PRG) with volume-shear deformation (VSD) of materials; – “Drum ball mill” (DBM) with internal energy exchanging devices (IED).

Mechanoactivation of brittle materials (pre-preparation stage – for the production of nanostructured materials) was implemented in the process complex “PRG with VSD – vibration-centrifugal unit (VCU) – Vortex-acoustic dispersants (VAD)”. The processing facility can operate in open and closed grinding cycles for processing a wide range of man-made materials, including mining and processing enterprises – quartz-iron-containing waste of mining and processing plant.

The analysis of modern grinding systems and equipment [8]: drum ball mills in open and closed grinding cycles, medium-flow (roller, roller-pendulum, etc.); vibration, countercurrent, annular jet mills and others indicate that a variety of grinders characterized by high metal consumption, significant specific energy consumption (from 40 to 100 – 200 kWh or more).

In addition, the results of research and technical developments [9 – 13] indicate the feasibility of implementing unused reserves:

- organization of step-by-step grinding and ensuring selective (selective) dynamic effect of working bodies on the material;
- rational implementation of kinetic regularity at each grinding stage: maximum grinding speed at the first stage and exponentially changing - at the last stages with minimization of values of increasing energy consumption;
- realization of volume-shear deformation (VSD) or crush-shear (CSD) particles at the first stage in roller machines providing microdefect structure in both open and closed grinding cycles;
- an integral combination of various methods of destruction of microparticles (mechanical, physicochemical, aero or hydrodynamic, ultrasonic, etc.) at each stage of the technological process, etc.

It is advisable to use these technologies and equipment to support various innovative technologies: mechanoactivation of natural and man-made materials, preparation of initial materials for the production of nanostructured composite mixtures and products from them; development of additive processes in biochemical, architectural-construction, powder metallurgy, energy and other industries [13 – 17].

The analysis of analytical expression (1) characterizing kinetic law of change of fineness of milled material by time

$$\frac{dR}{dt} = -KR, \quad (1)$$

as well as experimentally confirmed patterns of dependence of content of large fractions R_i on grinding time t

$$R_i = R_0 \exp\left(-\left(\frac{t}{t_0}\right)^m\right), \quad (2)$$

indicate the exponential nature of the kinetics of the grinding process of various materials, as well as the decreasing values of the dispersion rate of particles, where R is the residue on the control sieve; m , k , t_0 are parameters of the equations that determine the nature of the dependence; K is the constant of the grinding rate – the ratio of the weighted average particle diameter of the material $d_{\text{avg.weight}}$ to the grinding time (tangent of the inclination angle φ_2 tangent to the grinding kinetics curve – $\text{tg } \varphi_i = \frac{d(d_{\text{avg.weight}})}{dt}$) at each stage (Fig. 1).

According to numerous studies carried out at the first stage of grinding materials of different grinding capacity, the K_φ grinding rate constant has maximum values.

Destruction of large particles occurs at the places of dislocation of structure defects (anisotropy, the presence of microcracks and residual stresses, etc.).

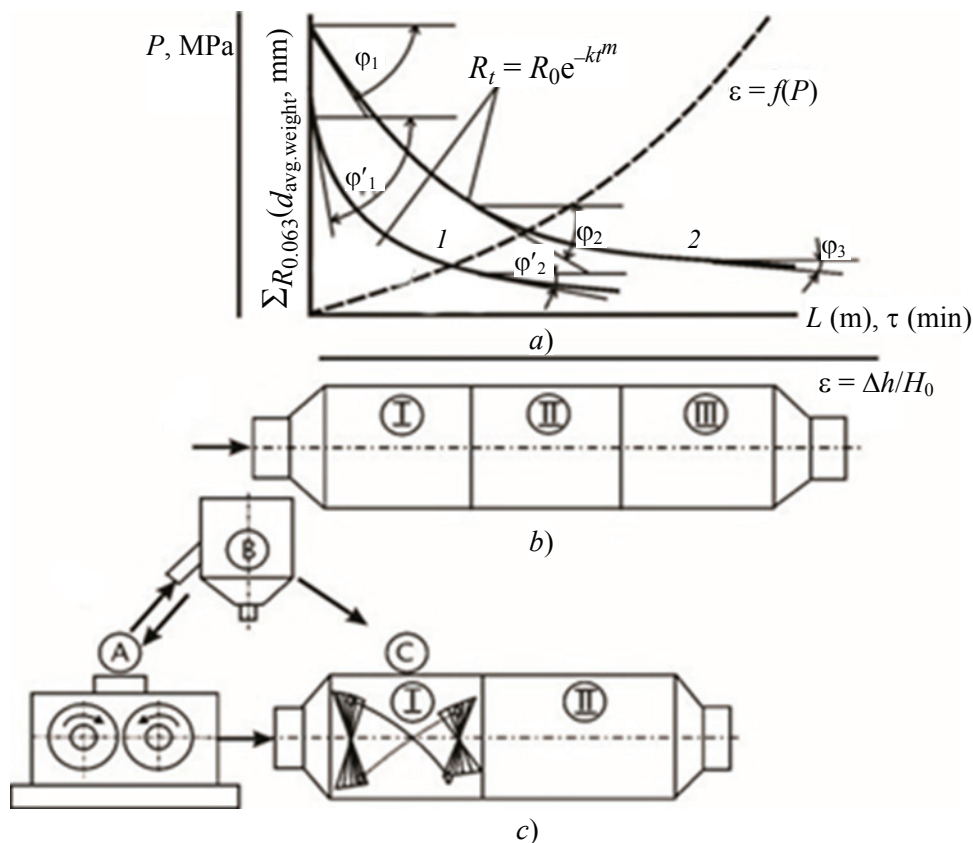


Fig. 1. Diagram of step-by-step grinding of materials in the process complex “PRG-DBM with IED”:

a – kinetics of grinding processes

(1 – in pipe ball mill, \sum_{R_i} , $d_{\text{avg.weight}} = f(L)$; 2, 3 – in PRG, \sum_{R_i} , $d_{\text{avg.weight}} = f(t)$; $\varepsilon = f(P)$);

b – grinding stages in PBM; c – grinding stages in “PRG-DBM” energy saving complex

The effectiveness of subsequent particle destruction is largely determined by the microdefectivity of the particles achieved in the first stage, which depends on the nature and type of application of force loads. For the implementation of crushing-shear and volume-shear deformation of particles, the most favorable conditions are created in a press-roll grinder (PRG) with a conical profile of rolls and a reinforced surface of working elements or removable elements – lining (Fig. 2a).

It is known [18] that comparable specific energy consumption (when grinding Portland cement clinker to $S = 300 \text{ m}^2 \cdot \text{kg}^{-1}$) are: at RSD particles – $2.5\text{--}5.8 \text{ (kWh} \cdot \text{t)} \cdot \text{t}^{-1}$; at free impact – $23\text{--}58 \text{ (kWh} \cdot \text{t)} \cdot \text{t}^{-1}$; in case of combined impact – $32 \text{ (kWh} \cdot \text{t)} \cdot \text{t}^{-1}$.

The grinding efficiency in PRG is $(50\text{--}70) \times 10^{-4} \text{ m}^2 \cdot \text{J}^{-1}$, in a drum ball mill (DBM) of combined impact – $(10\text{--}40) \times 10^{-4} \text{ m}^2 \cdot \text{J}^{-1}$.

At the same time: \sum_{R_i} is total residue of ground

particles of specified size on the sieve, %; $d_{\text{avg. weighi}}$ is weighted average particle size, μm ; L is length of pipe ball mill (PBM) or drum ball mill (DBM), m; ε is relative deformation of ground layer of particles with height H_{0i} (mm) in PRG – $\varepsilon = \frac{\Delta H}{H_0}$; ΔH is

absolute deformation of the layer, mm.

In subsequent grinding steps (Fig. 1a, curve 1), the grinding resistance of the particles increases, respectively, the grinding rate constant – $K_{\varphi_3} \ll K_{\varphi_2} < K_{\varphi_1}$. There is a significant increase in energy consumption. This is due to spontaneous aggregation of polydisperse particles due to autohesion and electrostatic interaction corresponding to irrational energy dissipation in the ground medium;

lack of segregation of fine and coarse particles, as well as separation of the crushed product, etc.

In connection with the above-mentioned very efficient energy-saving technology, the implementation of a step-by-step grinding process is: PRG – the first stage, DBM with internal energy exchange devices (in the form of two-start screw blades – 2SSB) – the second stage (Fig. 2a, b). The use of PRG at the first stage provides at lower power consumption ($q = 2\text{--}5 \text{ (kWh} \cdot \text{t)} \cdot \text{t}^{-1}$) and the grinding time of the microdefect particle structure for subsequent refinishing of the materials in the DBM with the IED. Energy-exchanging devices destroy “dead zones” (30–40 %) of the grinding load of DBM, intensify the classification and internal recycling of the ground material, allow to reduce the mass of grinding bodies to 20 %, and, therefore, the power consumption of the drive. Ultimately, this enables to reduce the energy consumption for grinding by 20–30 %.

The efficiency of the grinding process is also facilitated by the implementation in the grinding system of the external recycling of the material of the closed grinding cycle in the following sequence: straight – $A \rightarrow B$, $B \rightarrow C$ and reverse – $A \leftrightarrow B$ (Fig. 1c).

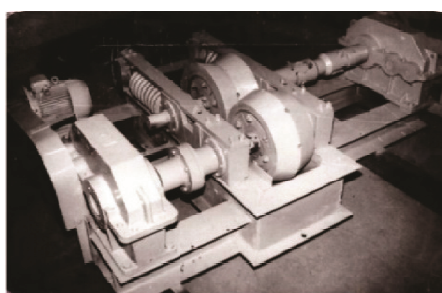
For these cases, the grinding rate constants are determined by the formulas:

– for the process $A \leftrightarrow B$

$$K_0 = -\frac{1}{t(K_p + 1) \ln \frac{R_B}{R_0}}; \quad (3)$$

– for the process $A \rightarrow B \rightarrow C$

$$K_A = -\frac{1}{t_A \ln \frac{R_A}{R_0}}; \quad K_B = -\frac{1}{t_B \ln \frac{R_B}{R_0}}, \quad (4)$$



a)



b)

Fig. 2. Energy-saving step-by-step grinding units:

a – PRG with conical roll profile ($D_{\text{av}} \times B = 0.7 \times 0.3 \text{ m}$, $\vartheta_{\text{env}} = 0.2\text{--}0.5 \text{ ms}^{-1}$, $N = 30 \cdot 10^3 \text{ W}$; $Q = \leq 6 \text{ t} \cdot \text{h}$, $v_{\text{sd}} = 70 \cdot 10^4 \text{ H}$); b – DBM with IED (\times) DBM = $2 \cdot 10.5 \text{ m}$; $G_{\text{m.t.}} = 28 \text{ t}$, $N_{\text{cons}} = 415 \times 10^3 \text{ W}$, $= 34 \text{ kWh}$, material – lime-silica charge)

where A is the starting material; B is intermediate size material; C is final material; K_0 is grinding rate constant for reverse and sequential processes; K_p is equilibrium constant equal to the ratio of the rate of direct and inverse processes.

The numerical values of these constants are complex criteria of the process of grinding materials by individual stages in a fairly wide range of dispersion of materials.

The above principles of organization of grinding process, performed scientific and technical developments, as well as unused technological reserves of grinding systems can be used as the basis of processes of mechanical activation of various materials, including for production of nanostructured composite mixtures.

The developed process facility involving step-by-step grinding of raw materials of low, medium and high strength ($d_0 \leq (20-30) \cdot 10^{-3}$ m) in energy-saving units, has the above advantages due to use of selective volumetric-shear deformation of material by PRG working elements – at the first stage, combined action of grinding charge in vibration-centrifugal unit – at the second stage and vortex-acoustic dispersion of microdeformed particles – at the third stage [19].

The grinding system can operate both in an open cycle (per pass) and in a closed cycle with external

recycling of ground materials during their separation and dust release.

The objects of the study were the waste of mining and processing enterprises - mine refuse ferruginous quartzite (MRFQ) of the tailings dump of Lebedinsky MPP KMA.

2. Materials and methods

The rock-forming mineral is quartz, magnetite, hornbeam, iron oxides, pyrite. The silica content of Lebedinsky tailings storage ranges from 47.50 to 75.08 % (Table 1). Most silica is associated with quartz and only a small amount of it is included in the silicates.

Iron oxides make up ore minerals – magnetite and hematite – are contained in small quantities in silicates. Their ratio in the tails of enrichment is different. The tails of Lebedinsky MPP (FeO) have high values of 6.26–10.71 % content.

Size distribution of tailings by doors is given in Table 2. An increase in the number of fine fractions (0.10–0.045 mm) is observed with the removal of pulp from the point of discharge and with the depth of extraction.

Mineralogical composition of investigated materials of Lebedinsky MPP was evaluated by results of X-ray phase analysis (Fig. 3).

Table 1. Chemical composition of Lebedinsky MPP waste, mass. %

| Fe _{main} | FeO | Fe ₂ O ₃ | SiO ₂ | CaO | MgO | Al ₂ O ₃ | MnO | P | S | TiO ₂ | Na ₂ O+K ₂ O |
|--------------------|-----------|--------------------------------|------------------|------|------|--------------------------------|------|-------|-------|------------------|------------------------------------|
| 10.3 | 6.26–10.7 | 3.5 | 69.35 | 2.93 | 4.95 | 2.13–2.53 | 0.09 | 0.163 | 0.204 | 0.168 | 1.33 |

Table 2. Mean values of fractional composition of tailings along the distribution dam crossbars as they are removed from the filling zone

| Meters | Particle size distribution by crossbars in mass, % | | | | | | | Average weight <i>D</i> , mm |
|--------|--|------|------|------|-------|-------|-------|---------------------------------|
| | 0.8 | 0.4 | 0.2 | 0.1 | 0.071 | 0.045 | < | |
| +20 | 4.6 | 27.4 | 35.2 | 8.93 | 12.2 | 2.10 | 9.57 | 0.334 |
| +40 | 2.3 | 18.3 | 35.1 | 12.3 | 16.6 | 3.00 | 12.40 | 0.271 |
| +60 | 3.4 | 15.5 | 31.3 | 13.4 | 19.4 | 4.40 | 12.60 | 0.256 |
| +80 | 3.8 | 21.2 | 34.0 | 11.1 | 15.7 | 1.96 | 12.24 | 0.294 |
| +100 | 2.4 | 8.60 | 28.2 | 18.2 | 23.8 | 3.53 | 15.27 | 0.208 |
| +200 | 2.7 | 11.6 | 30.8 | 16.5 | 20.4 | 2.90 | 15.00 | 0.231 |

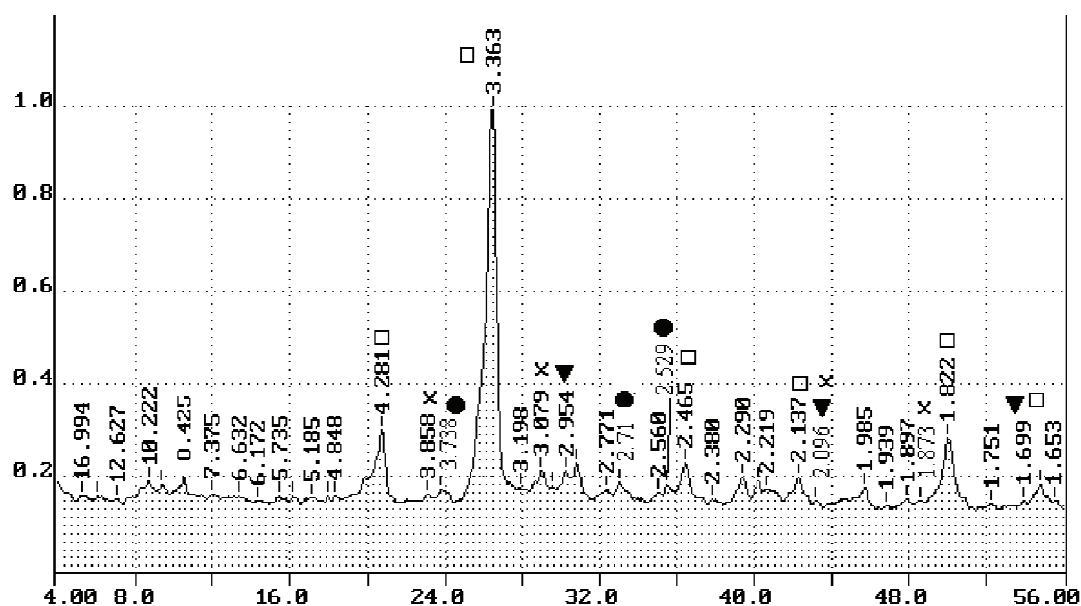


Fig. 3. X-ray images of the initial TEFQ of Lebedinsky MPP

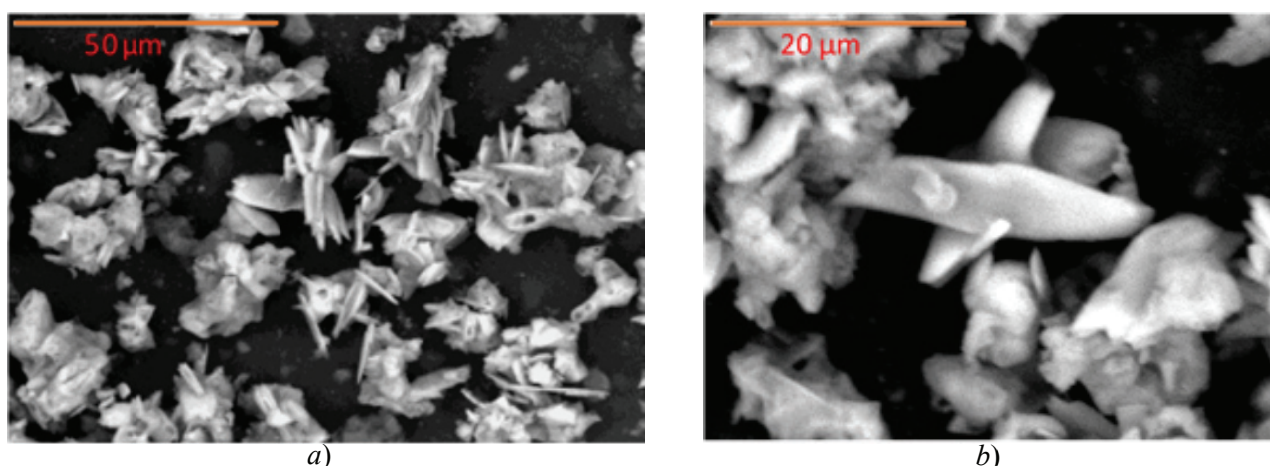


Fig. 4. Samples of Lebedinsky MPP waste with an increase of 500 (a) and 2000 (b) times

To obtain more complete information on the physicochemical properties of the mineral, microscopic studies of wet magnetic separation wastes were carried out on a scanning electron microscope (SEM) JSM-5300 (Japan) according to the corresponding method. The results of the studies (Fig. 4) showed that the sample of TEFQ waste consists of dust-like particles with sizes from 5 to 30 μm and their aggregates reaching 100 μm or more.

Thus, according to the chemical and mineralogical compositions, TEFQ can be attributed to quartz-containing waste with impurities of iron oxides. The waste is represented as highly ferrous artificial sands, which, according to G.S. Khodakov [20], can be used to produce quartz-based iron oxide filler pigments.

3. A waste processing technology and obtaining iron-containing filler pigment based on it

Many industrial wastes have a polymorphism – the ability of a substance of the same composition, depending on external conditions, to exist in several crystalline forms (polymorphic modifications) with different structures. The external conditions that determine polymorphism include, first of all, temperature and pressure. Therefore, each polymorphic modification has its own region of temperatures and pressures at which it exists in a thermodynamically stable state, and when changed, it loses stability and exists in a non-equilibrium state.

One method of producing inorganic pigments is by reactions that occur on the surface of the solid phases. The synthesis of pigments occurs at a high

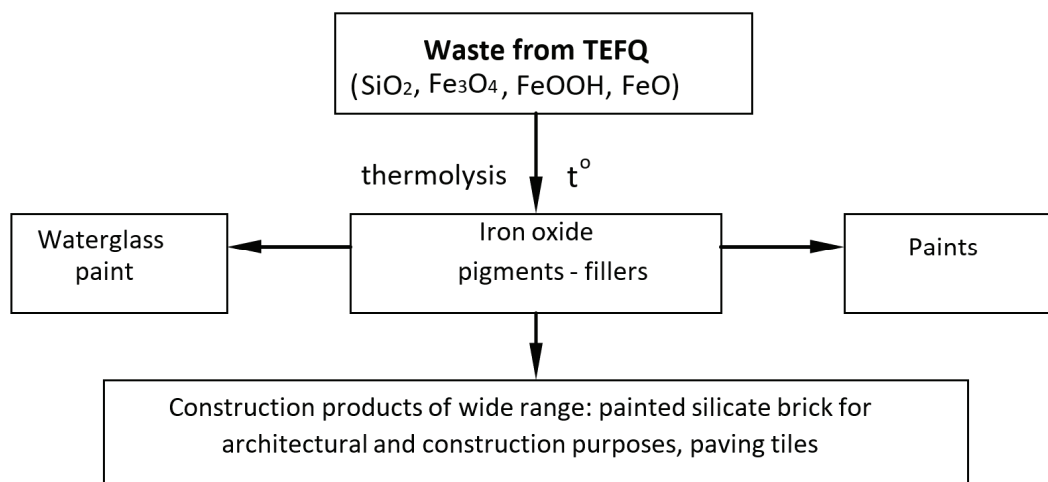


Fig. 5. Recovery scheme of metal-containing wastes of KMA

temperature and is accompanied by complex processes occurring in solid mixtures when heated, including a number of steps: 1 – occurrence of defects of crystal lattice loosening; 2 – formation, consumption of solid solutions; 3 – restructuring due to polymorphic transformations; 4 – diffusion (external, internal, surface); 5 – sintering, recrystallization; dissociation; 6 – chemical interaction of initial components.

The rate of solid phase reactions depends on the temperature, the duration of holding at the final firing temperature, as well as the surface of interaction between the constituent reagents.

Based on the above studies, a waste processing technology was developed using thermolysis and obtaining iron-containing filler pigment based on it (Fig. 5). A distinctive feature of the proposed technology is the combination of “heat treatment-grinding” processes with obtaining pigments-fillers.

The manufacturing process of filler pigments includes the following steps:

1. Pre-dispersing the paint components according to a given formulation.
2. Final grinding.
3. Preparation of filler pigment during roasting of waste products at 500–1000 °C temperature for 1 hour.

To implement this technology, we used theoretical and experimental studies, design and technological developments to create energy-saving units of selective effect.

We have developed a process line for the production of highly dispersed iron oxide filler pigments based on TEFQ (Fig. 6). The main technological stages of processing of iron-containing

technogenic materials are: preliminary preparation of raw materials (classification, drying, thermal treatment), fine or ultra-fine dispersion of materials with their subsequent separation, mixing of the composite mixture (if additional components are necessary), etc. [21–23].

In the first stage of grinding, PRG was used for preliminary destruction of the material (Fig. 2a). The efficiency of using the preliminary grinding of material in PRG before they are milled in the mill is not only due to the rational way of realizing energy costs with the direct crushing and shear effect of the working bodies (rolls) on the material to be destroyed, but also providing microdefect structure of particles, which reduces specific consumption of electric energy at final domole of the material in the mill, including in VCU [24].

A distinctive feature of the VCU (Fig. 7) is the combination of medium, thin and ultra-fine grinding stages in one process machine, which is provided by various camera paths for the corresponding grinding load operation modes: for medium grinding (less than 100–150 μm) – intense impact load and partial abrasion; for fine grinding (less than 50 μm) – impact load with increasing degree of abrasion; for ultra-fine grinding (less than 20 μm) – intensive abrasion [8, 9].

Obtaining a product of less than 5 μm in mechanical units is very difficult. In the vortex-acoustic disperser (Fig. 8), the principle of “self-destruction of particles from the inside” is used during grinding. Particles are destroyed by complex action in high-speed vortex flows ($V = 50\text{--}250\text{ ms}^{-1}$ and more) [25, 26], characterized by zones of discharge and compression.

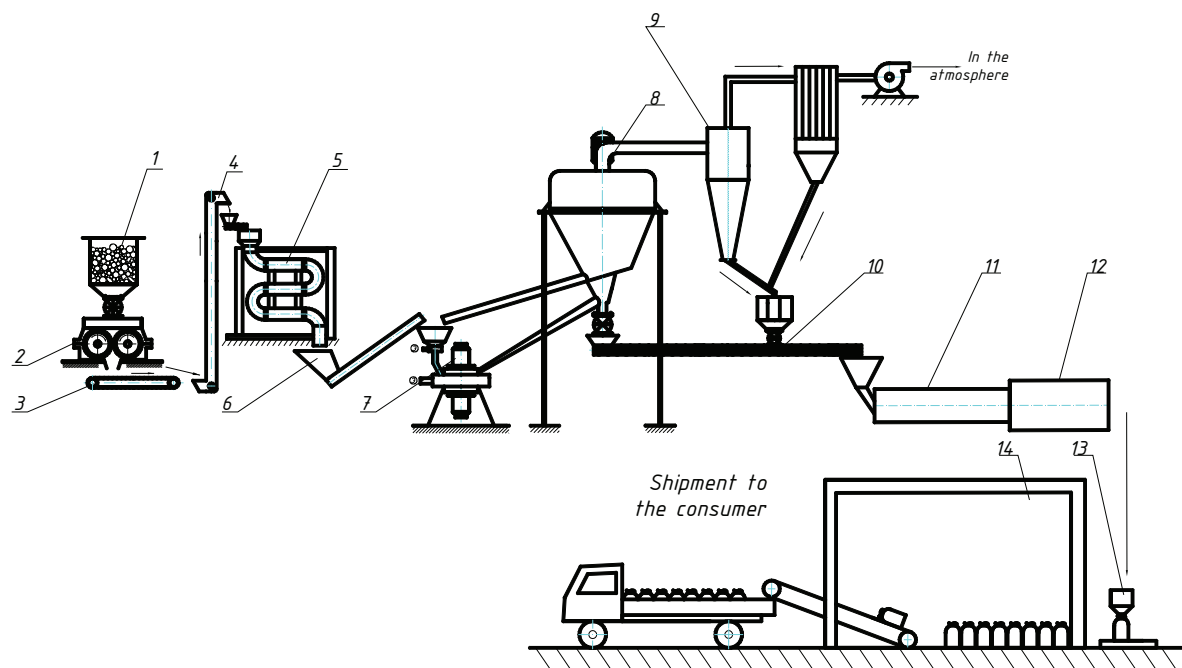


Fig. 6. Production line for production of finely dispersed pigments-fillers based on heat-treated wastes of TEFQ:
 1 – receiving hopper; 2 – press-roll grinder; 3 – tape feeder; 4 – elevator; 5 – vibration-centrifugal unit; 6 – compressor;
 7 – vortex-acoustic dispersant; 8 – separator; 9 – aspiration system; 10 – screw conveyor; 11 – furnace; 12 – refrigeration
 drum; 13 – packing machine; 14 – warehouse of finished products

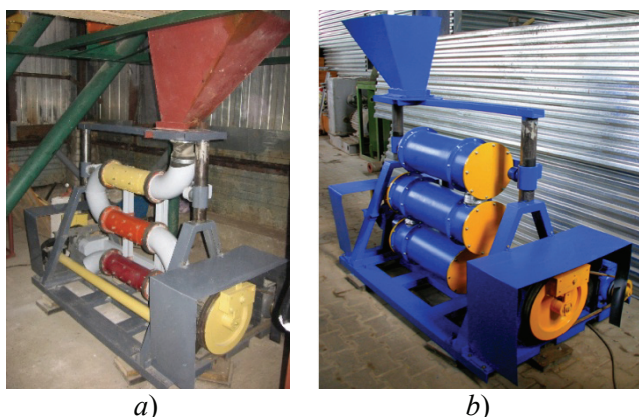


Fig. 7. Vibration-centrifugal unit:
 a – general view; b – grinding chambers

Technical characteristics of the experimental-industrial vibration-centrifugal unit (Fig. 7):

| | |
|--|---------|
| Capacity, kg·h ⁻¹ | 50–150 |
| Crank speed, rpm | 250–350 |
| Power consumption, kW | 1.1 |
| Eccentricity value, m | 0.02 |
| Volume of grinding chamber, m ³ | 0.01 |
| Overall dimensions, mm: | |
| length | 2202 |
| width | 816 |
| height | 1290 |

The raw material from the separator enters the VAD grinding chamber through the loading funnel (Fig. 8). It is mixed with energy carrier supplied from

distributing receiver through nozzle. Jets of energy carrier, breaking out of nozzles, accelerate movement of material particles. Near the cavity resonators vortices are created, which facilitate grinding of material in a two-phase flow due to multiple collisions between jets in the grinding chamber. Zones of sound and/or ultrasonic oscillations transverse to rotating vortex flow are created.

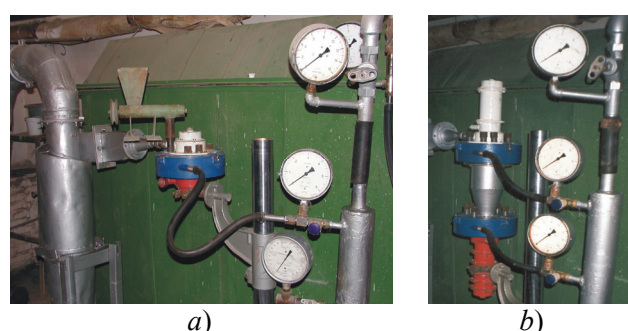


Fig. 8. Designs of vortex-acoustic dispersant:
 a – with one grinding chamber, b – with two material grinding chambers and intermediate separation unit

Technical specifications of trial samples of vortex-acoustic dispersants (Fig. 8):

| | |
|--|----------|
| Capacity, kg·h ⁻¹ | up to 35 |
| Specific consumption of energy carrier, kg per kg | 0.65–0.8 |
| Operating pressure, MPa | 0.2–0.5 |

| | |
|---------------------------------------|------------|
| Weighted average diameter: | |
| finished product, μm | $\leq 1-5$ |
| Grinding chamber diameter, m | 0.14 – 0.2 |
| Overall dimensions, mm: | |
| height | 1500 |
| width | 400 |
| length | 600 |

The ground material is moved under the action of centripetal forces to the central zone of the grinding chamber and further to the dust settling device.

Improved efficiency of fine grinding of materials is ensured due to possibility of changing frequency of acoustic oscillations in grinding chamber. VAD has rational technological arrangement of grinding chambers. Due to the operation of the unit in a closed grinding cycle, minimal dust release into the environment is ensured.

Based on the results of the tests of the TEFQ waste grinding process, the following indicators were obtained (Table 3).

The factors that have the greatest influence on the output parameters of the grinding process efficiency have been established: $P_{\text{main}} = 0.3-0.4$ MPa; nozzle cross-sectional area $F = 40-60$ mm²; width of resonators $b = 2.5-3.0$ mm (Fig. 9).

Using the developed technological line of step-by-step grinding, tests were carried out on a vortex-acoustic dispersant equipped with acoustic oscillation resonators for the production of pigments-fillers for oil paints (Russian Standard 10503–71).

Experimental studies confirm the effectiveness of step-by-step grinding of materials in the PRG-VCU-VAD system.

Final formation of pigments-fillers with specified color and physicochemical properties is achieved during firing (Table 4).

Table 3. Results of trial tests*

| Material | PRG | | | VCU | | | VAD | | |
|-------------|--|--|------------------------------|-----------------------------|--|------------------------------|-----------------------------|--|------------------------------|
| | $Q \cdot 10^3$, kg·h ⁻¹ | S , m ² kg ⁻¹ | q , kWh·t ⁻¹ | Q , kg·h ⁻¹ | S , m ² kg ⁻¹ | q , kWh·t ⁻¹ | Q , kg·h ⁻¹ | S , m ² kg ⁻¹ | q , kg·kg ⁻¹ |
| TEFQ wastes | up to 2 | – | 3 | 100 | 540 | 11 | 35 | 1260 | 1.7 |

* Q – efficiency; S – specific surface area; q – power consumption.

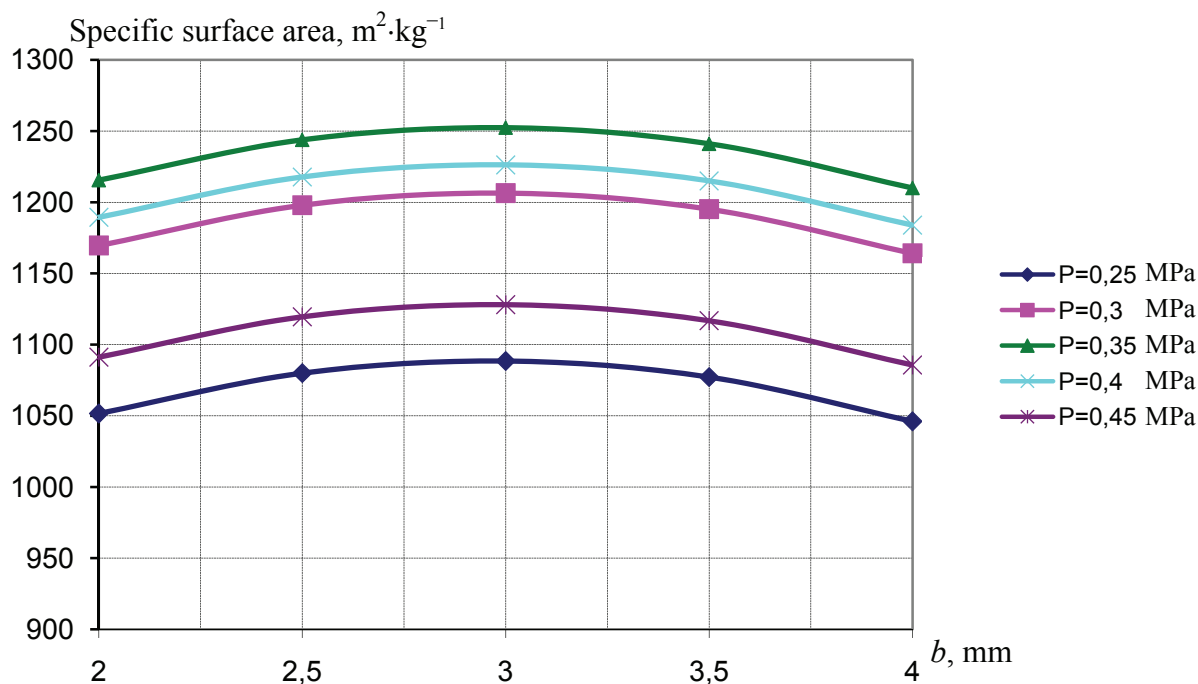


Fig. 9. Influence of resonator width and energy carrier pressure efficiency of grinding process

The most important characteristics of pigments are: color, its saturation and brightness, light resistance. These parameters were determined on the FKCSH–M comparator (Table 5). Oily paints based on TEFQ wastes have universal adhesion to concrete,




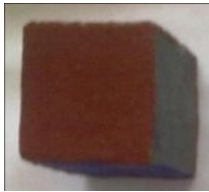












brick, natural stone, asbestos cement; have a high affinity for the listed materials.

Table 5 shows samples of colored surfaces of various materials with a coloring agent based on TEFQ.

Table 4. Optical characteristics of pigments based on TEFQ wastes depending on firing temperature

| Temperature processing, °C | Tristimulus coefficients | | | Chromaticity coefficients | | | Color Options | | |
|----------------------------|--------------------------|----------|----------|---------------------------|----------|----------|----------------------|---------------------------|-------------------------|
| | <i>X</i> | <i>Y</i> | <i>Z</i> | <i>x</i> | <i>y</i> | <i>z</i> | Brightness, <i>B</i> | Color tone λ , nm | Saturation <i>P</i> , % |
| 500 | 3.92 | 4.91 | 0.010 | 0.44 | 0.55 | 0.0012 | 0.65 | 575 | 38 |
| 800 | 4.83 | 4.59 | 0.008 | 0.52 | 0.49 | 0.0009 | 0.70 | 580 | 39 |
| 900 | 4.82 | 4.58 | 0.008 | 0.51 | 0.48 | 0.0009 | 0.70 | 580 | 40 |
| 1000 | 5.46 | 2.75 | 0.004 | 0.65 | 0.34 | 0.0007 | 0.66 | 609 | 40 |

Table 5. Painted Surface Samples

| Material | Temperature processing, °C | | | |
|----------|---|--|---|---|
| | 500 | 600 | 700 | 1000 |
| Concrete |  Dark brown |  Brown |  Henna-red |  Dark red |
| Brick |  Dark brown |  Brown |  Henna-red |  Dark red |
| Glass |  Dark brown |  Brown |  Henna-red |  Dark red |
| Wood |  Dark brown |  Brown |  Henna-red |  Dark red |

It was found that the physicochemical properties of the obtained pigment are not inferior to those of classic commercial iron oxide pigments consisting of 95–98 % of α -Fe₂O₃. The latter are widely used in the paint and varnish industry; for painting plastic masses, linoleums, as well as as pigments-fillers in paints, enamels, etc. Replacing the expensive classical pigment with a material based on ferruginous quartzite tailings is techno-cost effective.

4. Conclusions

Using the fundamental kinetic regularities of the processes of changing the grinding rate of materials with various degree of dispersity, a resource-saving technology for the complex processing and mechanoactivation of man-made charges was developed. Patent-protected structures of energy-efficient grinding units for selective grinding of materials at each stage of their processing have been developed and tested in production conditions: at the first stage – PRG, which provide volume-shear deformation of fine materials and obtaining a microdefect structure of ground particles; at the second stage – drum ball mills with internal energy exchange devices implementing combined impact-crushing-abrading effect of grinding medium with reduction of its mass (consumed power) by 10–20 %.

For mechanoactivation of small-sized materials and production of nanostructured mixtures, technological complexes were developed: PRG-VSD – vibration-centrifugal grinding units – vortex-acoustic dispergators, which provide, with the use of mechanical-aerodynamic and acoustic action, the production of ultradisperse particles < 5 μ m for their subsequent nanostructuring. The results of scientific and technical developments were used in the experimental and industrial testing of resource-energy-saving technology and the production by a mechanical and thermal method of pigments-fillers of a wide color scheme from quartzite-iron-containing wastes of the concentration plant of the Lebedinsky MPP.

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6. Conflict of interests

The authors declare no conflict of interest.

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