

Research into the crushing and grinding processes of iron ore with its simultaneous effect by mechanical load and electric field of ultra-high frequency

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Abstract. Main properties of the processes of iron ore destruction in terms of its simultaneous effect by mechanical load and electric field of ultra-high frequency have been studied. That was compared with the case when only mechanical load is applied. Theoretically, it has been proved that in the first case, quartz crystals accumulate more energy, and this effect is manifested mostly in terms of resonance. For the first time, the iron ore samples of cubic geometry were tested using a non-uniform volumetric compression unit. Application of the ultrahigh frequency field resulted in ultimate strength reduction by 1.5 – 2.0 times and significant increase in plasticity of the destruction. At the same time, density of the sample destruction energy in a volume unit is significantly lower than that in the case of mechanical load (1.05 and 2.6 MJ/m³, respectively). There is also a tendency of reducing large fraction yield and increasing fine fraction yield along with the increase up to 11% in iron content in the products after grinding. The results of theoretical and numerous experimental studies have been substantiated the necessity to continue the research and development work on adapting the proposed jaw crusher to the production conditions.

1 Introduction

The effectiveness of simultaneous effect of mechanical load and electric field of ultra-high frequency (UHF) in the process of iron ore crushing is substantiated in theoretical and experimental ways. Chemical analysis of the grinding products should be carried out. It is proposed to customize a jaw crusher for the production conditions implementing this method. An integrated approach comprising physical phenomena studies, laboratory tests, and chemical analysis is considered to be a methodological basis to solve that task. Statistical studies of the experiment results should be done. Testing of iron ore samples for uniaxial and bulk unequal component compression accompanied by UHF electric field has helped determine a tendency to obtain more intensive crushing with the reduced critical load. In such a case, iron content in a final grinding product increases up to 11%.

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For the first time, the research proposes to apply inverse piezoelectric effect in the process of mechanical crushing and grinding of iron ore. Functions of absorption and dispersion amplitudes are obtained from the vector equation of a harmonic oscillator. Analysis of those functions has allowed making conclusion on the resonance under which a quartz crystal absorbs maximum energy. A technique to test cubic samples in a non-uniform volumetric compression unit equipped with a UHF generator has been developed. Basic characteristics of the sample behaviour while testing up to its ultimate strength and beyond its limiting state with the recording of “stress-strain” diagram have been studied. Chemical analysis of iron ore grinding products during mechanical destruction with and without application of UHF field has been carried out; statistical analysis of the obtained results has been performed as well. Efficiency of using UHF electric field during mechanical crushing and grinding of iron ore under production conditions has been proven. A patent of Ukraine for a jaw crusher design implementing simultaneous impact of mechanical load and UHF electric field on iron ore has been received. Further research and development work on its use at a certain stage of iron ore grinding has been substantiated technically.

A method to crush quartz-containing rocks (e.g. iron ore) providing simultaneous effect of mechanical load and UHF electric field has been developed in Dnipro University of Technology [1]. Samples of regular geometry have been tested for uniaxial and triaxial compression [2]; iron ore samples of arbitrary geometry have been tested in a laboratory crusher [3]. The obtained results have confirmed the method efficiency. Chemical analysis of the products of iron ore crushing and grinding in terms of different loading methods has been initiated [5]. A sampling method was used for each case of laboratory or industrial research; in this context, sample representativeness was provided by a number of samples specified according to the statistics rules [6]. A jaw crusher design implementing a method of simultaneous impact of mechanical load and UHF electric field on iron ore has been proposed [7, 8].

Technological cycle of iron ore crushing and grinding under production conditions is possible only in terms of mechanical load being rather labour-consuming and energy-intensive. Application of physical impact methods on iron ore to intensify its crushing and grinding processes is still at the stage of research and development [9].

2 Solution of vector equation of a harmonic oscillator

Iron ore is known to be a complex medium with a polycrystalline structure; therefore, its electromagnetic properties are determined by the aggregate properties of the constituent crystals. Confine to the first approximation, where the medium is assumed to consist only of quartz crystals and each grain has an electrical axis (piezo-axis). Such an assumption makes it possible to take into account both direct piezoelectric effect and reverse piezoelectric effect [10], if iron ore is effected by the mechanical load and UHF electric field. Quartz belongs to ionic crystals and, any of its atoms or ions can interact equally strongly with all the adjacent atoms or ions; thus, the whole crystal can be considered as a separate molecule. On the other hand, each quartz crystal has a set of resonant frequencies. The accepted assumption allows using a harmonic oscillator model. The influence of an electromagnetic field and mechanical load causes the oscillator to perform forced oscillations and become equivalent to an electric dipole, which moment is proportional to the electric field strength and the applied force of the mechanical load.

Use mathematical model [11, 12] of the harmonic oscillator [13]:

$$M(\vec{r})'' + M\gamma(\vec{r})' + M\omega_0^2\vec{r} = \vec{F}_{ext}, \quad (1)$$

where \vec{r} is relative displacement of the crystal lattices of positive and negative ions; γ is friction coefficient; ω_0 is cyclic frequency of the oscillator; \vec{F}_{ext} is external driving force; M is reduced mass of ions, determined by the formula:

$$M = \frac{M_{poz} \cdot M_{neg}}{M_{poz} + M_{neg}}, \quad (2)$$

where M_{poz} and M_{neg} are total mass of positive and negative ions respectively.

Equation (1) is represented by the following system of three scalar equations for each coordinate axis:

$$\begin{cases} Mx'' + M\gamma x' + M\omega_0^2 x = F_{ext,x}; \\ My'' + M\gamma y' + M\omega_0^2 y = F_{ext,y}; \\ Mz'' + M\gamma z' + M\omega_0^2 z = F_{ext,z}. \end{cases} \quad (3)$$

Direct axis Oy along the line of the mechanical force action and confine to the analysis of crystal deformation along this direction, using the second equation of the system (3):

$$My'' + M\gamma y' + M\omega_0^2 y = F_{ext}. \quad (4)$$

Polarization charges arising on the crystal surface are proportional in the linear approximation to the mechanical force [14]:

$$q = \alpha_1 F, \quad (5)$$

where F is mechanical force effecting the crystal; α_1 is proportionality coefficient depending on the piezo axis orientation of the quartz crystal relatively to axis Oy .

The force effecting a quartz crystal as a result of the direct piezoelectric effect is as follows:

$$F_{dir} = qE, \quad (6)$$

where E is electric field intensity.

Taking into consideration (5), we obtain:

$$F_{dir} = \alpha_1 EF. \quad (7)$$

The force arising from the inverse piezoelectric effect is:

$$F_{rev} = \alpha_2 E, \quad (8)$$

where α_2 is proportionality coefficient.

Forces F_{dir} , F_{rev} , and F determine totally the external exciting force, therefore:

$$F_{ext} = F_{dir} + F_{rev} + F. \quad (9)$$

By applying (7) and (8), we obtain:

$$F_{ext} = \alpha_1 EF + \alpha_2 E + F. \quad (10)$$

In terms of that model, deforming forces, resulting in electrostriction, are not taken into account since the components of deformation tensor, depending on the electric field

strength, are of quadratic forms.

If the electric field effecting the crystal experiences sinusoidal changes in time, then:

$$E = A_0 \cos \omega t, \quad (11)$$

where A_0 is electric field amplitude; ω is cyclic frequency of oscillation.

Mechanical force is as follows:

$$F = P \nu t, \quad (12)$$

where P is value of the applied mechanical load; ν is load application velocity.

Taking into account (11) and (12), external driving force (10) is as follows:

$$\vec{F}_{ext} = F_1 t \cos \omega t + F_2 \cos \omega t + F_3 t, \quad (13)$$

where $F_1 = \alpha_1 A_0 P \nu$, $F_2 = \alpha_2 A_0$, $F_3 = P \nu t$.

Substituting (13) in the right-hand side of expression (4), we obtain the equation of a harmonic oscillator:

$$M y'' + M B_3 y' + M \omega_0^2 y = F_1 t \cos \omega t + F_2 \cos \omega t + F_3 t. \quad (14)$$

Solution of equation (14) is found in the form of:

$$y = (A_1 t + B_1) \sin \omega t + (A_2 t + B_2) \cos \omega t + (A_3 t + B_3), \quad (15)$$

where $A_i, B_i, i = \overline{1,3}$ are unknown coefficients.

To define them, we substitute function (15) and its derivatives into equation (14) and solve the resulting system of equations. We believe that the attenuation is weak ($\gamma \ll \omega_0$).

Thus, we obtain:

$$A_1 = \frac{F_1}{M} \cdot \frac{\gamma \omega}{(\omega_0^2 - \omega^2)^2 + \gamma^2 \omega^2}; \quad B_1 = \frac{F_2}{M} \cdot \frac{\gamma \omega}{(\omega_0^2 - \omega^2)^2 + \gamma^2 \omega^2};$$

$$A_2 = \frac{F_1}{M} \cdot \frac{\omega_0^2 - \omega^2}{(\omega_0^2 - \omega^2)^2 + \gamma^2 \omega^2}; \quad B_2 = \frac{F_2}{M} \cdot \frac{(\omega_0^2 - \omega^2)^2}{(\omega_0^2 - \omega^2)^2 + \gamma^2 \omega^2};$$

$$A_3 = \frac{F_3}{M \omega_0^2}; \quad B_3 = 0.$$

Then solution (15) is as follows:

$$y = \frac{F_1 t + F_2}{M} (A \sin \omega t + B \cos \omega t) + \frac{F_3 t}{M \omega_0}; \quad (16)$$

where $A = \frac{\gamma \omega}{(\omega_0^2 - \omega^2)^2 + \gamma^2 \omega^2}$; $B = \frac{\omega_0^2 - \omega^2}{(\omega_0^2 - \omega^2)^2 + \gamma^2 \omega^2}$.

Constant $A_{ab} = \frac{F_1}{M} A$ in (16) is called the absorption amplitude, $A_{dis} = \frac{F_1}{M} B$ is dispersion amplitude (elastic amplitude). Names of the amplitudes explain that time-mean value of the power absorbed by the oscillator is determined by component $A_{ab} = \sin \omega t$. Component $A_{dis} = \cos \omega t$ makes a certain contribution to the instantaneous value of the

absorbed power $P(t)$. However, on average, its contribution during the cycle of steady-state oscillations is equal to zero.

In terms of resonance ($\omega = \omega_0$), amplitudes of dispersion $A_{dis} = 0$ and absorption A_{ab} reach a maximum value (Fig. 1).

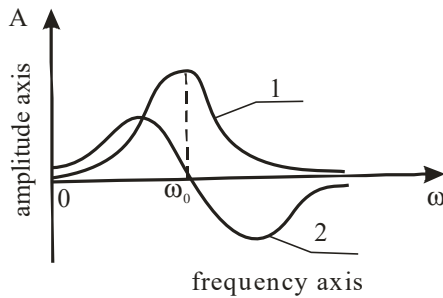


Fig. 1. Function graphs of the absorption (1) and variance (2) amplitudes.

3 Experimental studies

The energy accumulated by the oscillator is equal to the sum of its kinetic (E_{kin}) and potential (E_{pot}) energies:

$$E = \frac{1}{2}M((y')^2 + \omega_0^2 y^2), \quad (17)$$

where $E_{kin} = \frac{1}{2}M(y')^2$, $E_{pot} = \frac{1}{2}M\omega_0^2 y^2$.

Substitute the derivative of function y from equation (16) to equation (17) and retain only the non-oscillating part where the higher order addends are not taken into account. Then, the energy accumulated by quartz crystals, being effected simultaneously by mechanical load and UHF electric field, is:

$$E_j = \frac{D}{4M}(F_1 t + F_2)^2 + \frac{F_3^2 t^2}{2M\omega_0^2}, \quad (18)$$

where $D = \frac{\omega_0^2 + \omega^2}{(\omega_0^2 - \omega^2)^2 + \gamma^2 \omega^2}$, then:

$$E_{kin} = \frac{\omega^2 (F_1 t + F_2)^2}{4M((\omega_0^2 - \omega^2)^2 + \gamma^2 \omega^2)}, \quad (19)$$

$$E_{pot} = \frac{\omega_0^2 (F_1 t + F_2)^2}{4M((\omega_0^2 - \omega^2)^2 + \gamma^2 \omega^2)} + \frac{F_3^2 t^2}{2M\omega_0^2}. \quad (20)$$

Functions (18 – 20) have been studied; according to the following characteristic results: if $F_1 = 10^{-4}$ N, $F_2 = 0.5 \cdot 10^{-4}$ N, $F_3 = 10^{-5}$ N, $\omega = 40$ 1/s, $t = 60$ s, $M = 10^{-12}$ kg, $\gamma = 20$, graphs of energy dependence on proper frequency of the quartz have been plotted (Fig. 2).

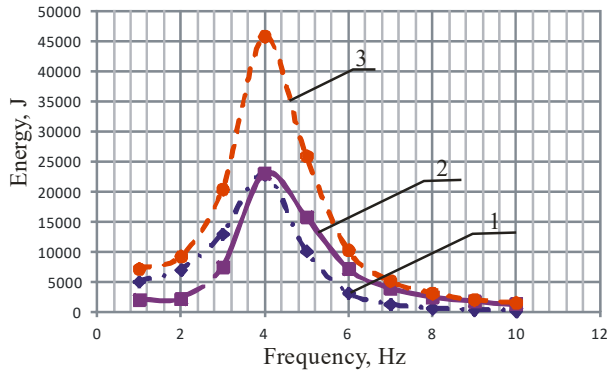


Fig. 2. Energy function (accumulated by a quartz crystal) from its proper frequency: 1 – kinetic energy, E_{kin} ; 2 – potential energy, E_{poi} ; 3 – general energy, E_j .

If $\omega_0 < \omega$, then kinetic energy exceeds potential energy (Fig. 2); in this case, electric field has more significant effect on the energy accumulation by a quartz crystal compared to the action of a mechanical load. If $\omega_0 > \omega$, the opposite phenomenon is observed; maximum value of the total energy is obtained in terms of $\omega = \omega_0 = 40$ 1/s.

Effect of UHF electric field as the additional energy source on the process of iron ore crushing was studied experimentally using a non-uniform volumetric compression unit [4]. Samples of cubic geometry with a side of 50 mm were tested; electric field was generated using a 70 W YB4-66 medical unit with the frequency of 40.68 Hz. Before the testing, rule of signs, strict numeration of the load axes, principal stresses σ_1 , σ_2 , σ_3 and their corresponding principal deformations ε_1 , ε_2 , ε_3 [15] were specified [15]. Simultaneous arrangement of UHF electrodes on all the sample faces is physically inexpedient, so the tests were carried out for uniaxial compression mode with minimal lateral support $\sigma_2 = \sigma_3$. The pressure was being increased along the axis σ_1 to the ultimate strength; sample destruction and its deformation were carried out until the value of residual strength was reached [8]. The tests carried out according to that method have demonstrated a decrease in tensile strength by 1.5 – 2.0 times and a significant increase in the plasticity of iron ore samples being destructed in terms of using UHF electric field compared with the effect of the mechanical load only (Fig. 3).

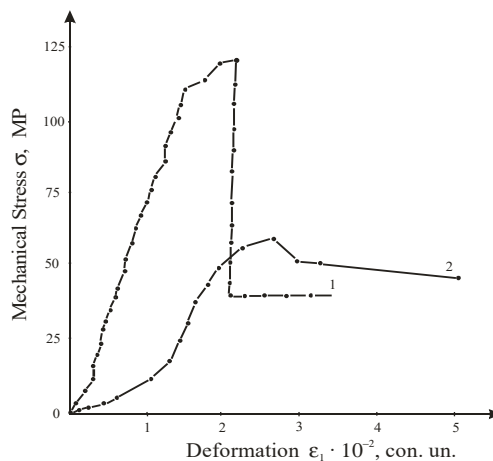


Fig. 3. “Stress – deformation” diagram when testing samples are of a cubic geometry: 1 – effect of mechanical stress only; 2 – simultaneous effect of mechanical load and UHF electric field.

It has been also found that in terms of simultaneous effect of mechanical load and electric UHF electric field upon the iron ore samples, the energy density of their destruction per volume unit is significantly lower than when only mechanical load is applied (1.05 and 2.6 MJ/m³, respectively).

It should be noted that the carried out studies do not allow evaluating the degree of iron ore crushing and the iron content in the grinding products. Quality indicators of the iron ore crushing and grinding processes were studied under the laboratory conditions using samples of arbitrary geometry (Horishni Plavni Field, Poltava region). It has been determined that they have resonance at frequencies of 41.5 – 43 MHz; besides, the resonant frequency with a series-connected inductance of 0.5 μ H is equal to 24.5 MHz; moreover, resonant properties at this frequency are stronger.

Taking into account the specified spectrum of ore resonant frequencies, technical task for designing a UHF generator has been developed. According to the task, a prototype was made with the adjustable frequency of 20 – 50 MHz and a maximum output power of 150 W. An experimental jaw crusher was also manufactured giving possibility to crush the fragments of an arbitrary geometry with maximum sizes of 60 – 80 mm and a crushing degree of 4 – 5. When a UHF generator is connected, it implements simultaneously mechanical loading and electric field with resonant frequency (Fig. 4).

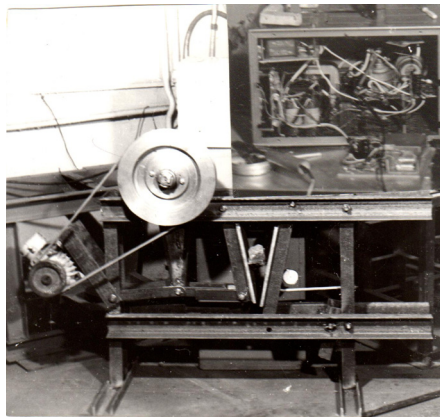


Fig. 4. Laboratory jaw crusher with a UHF generator.

To carry out laboratory experiments, ore of a relatively consistent composition was divided in pairs into groups comprising the samples of the same mass (Table 1).

Table 1. Conventional groups of iron ore samples.

Group number	1	2	3	4	5
Sample mass, g	1100	1000	700	600	180

A sample from each group was crushed by means of mechanical loading; then, the mechanical load and UHF electric field were used simultaneously on the experimental crusher.

Samples crushed according to the specified procedure were further crushed (up to fine particles) on a laboratory jaw crusher of DLSCH 150×80 type with a discharge gap of 3 mm. Using statistical processing of the results of those experiments [3] and numerical analysis [9], comparative data for each controlled crushing fraction have been obtained (Table 2).

Table 2. Granulometric composition of the products of iron ore fine crushing.

Group number	Load mode	Distribution of individual fractions in %, mm					
		+50	-50 +30	-30 +20	-20 +10	-10 +0.63	-0.03
I	Without UHF	18.8	35.0	17.0	14.8	0.4	14.0
	Applying UHF	24.9	35.1	13.8	13.6	0.6	12.0
II	Without UHF	21.9	33.3	16.7	15.3	0.5	12.3
	Applying UHF	28.3	35.5	13.9	12.0	0.5	9.8
III	Without UHF	18.9	35.5	16.0	16.2	0.5	12.9
	Applying UHF	11.9	30.7	20.0	19.8	1.0	16.6
IV	Without UHF	26.0	38.0	14.1	11.9	0.4	9.6
	Applying UHF	26.5	37.0	14.4	12.3	0.5	9.3
V	Without UHF	34.4	33.8	11.7	11.3	0.4	8.4
	Applying UHF	16.1	36.9	16.8	16.5	0.4	13.3
Average values	Without UHF	24.0	35.12	15.1	13.9	0.44	11.44
	Applying UHF	21.54	35.04	15.78	14.84	0.6	12.2
In % for crushing without UHF		82.75	99.77	104.5	106.76	136.36	106.6

Fine crushing products were ground in a ball mill of MBL – (75A – MS) type with the volume of 14 L with a degree of ball filling with $\varphi = 0.45$. The mill drum rotation speed $\vartheta = 0.7$ is critical; the grinding time was specified to ensure grinding size close to the first grinding stage at the mineral processing plant. The grinding products were divided into five classes. The iron content was determined in each class with further averaging of the results for that sample (Table 3).

Table 3. Data of granulometric and chemical analyses of iron ore grinding products.

Group number	Load mode	Size yield, %					Fe, %
		+4	-4 +2	-2 +1	-1 +0.63	-0.63	
I	Without UHF	0	7.2	16.0	15.7	61.1	41.8
	Applying UHF	0	5.5	15.1	11.2	68.2	44.3
II	Without UHF	0	12.2	16.8	13.5	57.5	26.7
	Applying UHF	7.5	16.2	15.0	10.2	51.1	27.0
III	Without UHF	0	6.3	16.3	13.8	63.6	21.3
	Applying UHF	0	2.7	11.2	11.0	75.1	25.3
IV	Without UHF	0	4.9	18.7	17.4	59.0	36.0
	Applying UHF	2.6	12.8	18.5	18.7	47.4	33.6
V	Without UHF	0	0	10.1	14.3	75.6	18.2
	Applying UHF	0	4.5	11.6	17.0	66.9	28.2
Average values	Without UHF	0	6.12	15.58	14.94	63.36	28.8
	Applying UHF	2.02	8.34	14.28	13.62	61.74	31.68

According to Tables 2 and 3, simultaneous action of mechanical load and UHF electric field results in the tendency of iron ore crushing intensification due to reduced coarse fraction yield and increased fine fraction yield; moreover, increase in iron content up to 11% in the grinding products is also observed. The results of theoretical and numerous experimental studies indicate real prospects for the development of efficient technologies for iron ore crushing and grinding under production conditions. Design of a new jaw crusher implementing the effect of UHF electric field on each monolithic unit located within its working space is proposed [7]. Further, research and design works on its use at one of the stages of iron ore crushing are planned.

4 Conclusions

Vectorial equation of a harmonic oscillator under the action of mechanical force is set; analytical expressions for the external driving force components are obtained.

Expressions for the amplitudes of absorption and dispersion are obtained. It has been defined that quartz crystals being simultaneously effected by mechanical load and electric UHF electric field, accumulate more energy than in case when only mechanical load is applied; that effect is manifested mostly in terms of resonance availability.

Experimental studies of the main characteristics of iron ore crushing in terms of cubic samples using non-uniform volumetric compression unit have been carried out. It has been determined that decrease of breakdown point by 1.5 – 2.0 times and significant increase of plasticity of the destructed samples are observed under the effect of UHF electric field as compared to the effect of only mechanical load. Energy density of the sample crushing per unit volume is also significantly lower (1.05 and 2.6 MJ/m³, respectively).

As a result of laboratory studies, it has been defined that, simultaneous action of mechanical load and UHF electric field results in the reduced coarse fraction yield and increased fine fraction yield; moreover, iron content in a final grinding product increases up to 11%.

To adapt a jaw crusher to the production conditions, it is necessary to continue studies on finding an effective way to supply UHF electric field into its working part.

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