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Microwave Heating for Emolliating and Fracture of Rocks

Aleksander Prokopenko
National Research Nuclear University MEPhI
Russia,
Moscow

1. Introduction

Fracture and emolliating of rocks has been traditionally used in the process of ore dressing. This process has always been given great attention. At the present stage of development of mining and processing industries except energy the efficiency of crushing rock and the increase the degree of extraction the problems arise preservation of individual inclusions crushed material or separation. Therefore, along with traditional methods of mechanical fracture investigates new ways of emolliating (loss of strength) and fracture of rocks based on different physical phenomena. These methods include: electrical (sputter-ion, electrostrictive and piezoelectric), magnetic (magnetostrictive), electromagnetic (laser), sound (impact plastic, ultrasonic), beam (electrons, protons and plasma) and thermal methods of destruction. Common to all methods of destruction is that as a result of such exposure in a material creates mechanical stresses. These stresses exceed fracture stress for most rocks. The stresses can lead to the formation of microcracks in the rock, which leads to a significant emolliating of rocks. Research on the electromagnetic effects on the rocks actively carried out in Russia. There have been many monographs devoted to new methods of destruction (Emelin, 1990), (Novik & Zilbershmitt 1996) and (Gridin & Goncharov, 2009).
Many of these methods can be used only for fracture of certain class of materials or have little capacity and selectivity. Thermal methods of destruction are rather promising. This method is limited to difficulties rapid heating of rocks at great depth because of the small coefficient of thermal conductivity. Conventional heating can not be uniformly and promptly heat the rock. From this point of view only using microwave heating can be achieved volumetric heating of the material at high speed. The majority of rocks are dielectrics with losses, which are well absorbed microwave energy. Microwave discharge on dissemination elements of rock caused by the high electric fields can also lead to its destruction.
Work on the use of microwave energy for the destruction and emolliating of rocks began in the USSR in the late 80's of the last century. It dealt mainly thermomechanical destruction of frozen soils (Nekrasov, 1979) and (Riabec, 1991). Revitalization of the work took place at the end of the 90's of last century, which is associated with the end of the Cold War, when many developments of powerful microwave electronics were unclaimed. In the Soviet Union have been created the most powerful and advanced generators of microwave frequencies, which power and efficiency is significantly faster than foreign. There were many recent trends of

microwave energy use: light sources based on microwave discharge, prompt microwave heating for fine destruction of coal, high-temperature microwave heating in the nuclear power, the use of pulsed microwave generators for cleaning and modification of metal surfaces, the use of microwave energy to fracture the kimberlites (Didenko, 2003), (Arkhangelsiy, 1998), (Petrov a, 2002) (Petrov b, 2002). (Didenko, en al., 2005).

Investigations on the emolliating and fracture of rocks by the microwave field are actively carried out abroad. In the last decade in the world issued more than 20 patents on microwave softening ore before grinding and removing the reservoir. Researches are made at universities and commercial organizations in Australia, USA, Canada, UK and Slovenia (Walkiewicz en al., 1991), (Tranquilla, (1998), (Lindroth en al., 1991), (Badhurst et al., 1990) and (Michal et al., 2010). Research is being carried in the direction of emolliating the iron and other ores before extraction or milling in order to ore-dressing. In (Salsman et al., 1996) the selectivity of the effects of microwave energy on the individual components of the rock and the experimentally growth of microcracks due to the thermomechanical stresses are displayed. A significant decrease in power consumption for milling and further separation of ferruginous ore after microwave treatment is shown in (McGill en al. 1988), (Walkiewicz en al., 1991). All researches note the perspectives of using microwave energy for emolliating and fracture of the rock.

The research is needed to find new methods of rocks destruction, which will allow better and more efficiently produce fracture and dressing of the rocks. The advantage of microwave processing of rocks before grinding may be increasing the selectivity of the disclosure of rocks. Preliminary microwave emolliating of rocks is the most effective for fine grinding rocks to improve the efficiency of separation of individual elements or dressing. Reduction of energy consumption and cost of equipment depreciation for fine grinding will contribute to increased formation of microcracks in the microwave processing of rock.

Paper purpose is to describe and analyze existing knowledge's about the processes of fracture and emolliating of rocks at microwave heating. Methods for measuring the dielectric characteristics of rocks, analysis of physical principles loss of strength and fracture of the rock, possible equipment for use in these processes, review of work done and the results of work on the destruction of the kimberlite at prompt microwave heating are presented in the paper. The author hopes that this paper will help to find new application of microwave energy.

2. Dielectric characteristics of rocks in microwave range

When working at microwave frequencies (300 - 30000 MHz) is necessary to know the electrodynamics characteristics of substances with which to work. They define the processes of absorption, reflection and the penetration of electromagnetic waves in a substance. For dielectric properties of minerals are divided into dielectrics (diamond, sulfur, fluorite, feldspar, etc.) and conductors or semiconductors (gold, graphite, pyrite, nickel, etc.). Dielectric loss in the first group is characterized by dissipation factor (dielectric loss tangent $tg\delta$). In the second group the power dissipation parameter is conductivity σ. Power absorbed in the dielectrics and conductors is proportional to an electric field intensity quadrate in them, as well as the permittivity, dissipation factor and conductivity, respectively. The inhomogeneity factor of the microwave heating of minerals within the rock depends on the dielectric properties of minerals. Nonuniform heating of minerals in the rock causing thermomechanical stresses, which lead to emolliating and destruction of the rock.

For rocks it is necessary to consider that the dielectric ε' and the magnetic μ' permeabilities of substance are complex. Typically the magnetic properties of materials in microwave range are feebly expressed μ'=1. It is necessary to consider only the complex permittivity ε'=ε(1-i·tgδ), where ε – permittivity (dielectric constant); tgδ - dissipation factor. The magnetic properties should be considered in ores containing ferromagnetic materials. Dissipation factor characterizes the losses in the dielectric due to polarization effects of molecules under the influence of electric field and the electronic and ionic conductivity. The majority of rocks belong to the class of imperfect dielectrics, for which the depth δ at which the value of the electric field is reduced to e=2.71828 times makes

$$\delta=\lambda/(\pi\cdot\varepsilon^{0.5}\cdot tg\delta), \quad (1)$$

where λ - wavelength of electromagnetic radiation. Thus, knowing the dielectric constant can be judged on uniformity of the rock heating by volume and effectiveness of this heating. Knowledge of the dielectric properties of the rock is necessary in the design and setting up installation for superprompt microwave heating.

Substance	Composition	ε (on axes a, b, c)	tgδ
Not polar minerals			
Diamond	C	5.7	$2\cdot10^{-4}$
Quartz	SiO_2	a 4.5, c 4.65	$2\cdot10^{-4}$
Chalcedony	SiO_2	4	10^{-4}-10^{-3}
Corundum	Al_2O_3	a 11, c 9	$5\cdot10^{-5}$
Rutile	TiO_2	a 88, c 170	$2\cdot10^{-4}$
Periclase	MgO	9.8	$4\cdot10^{-4}$
Halite	NaCl	5.9	$3\cdot10^{-4}$
Sylvite	KCl	4.4	10^{-4}
Fluorite	CaF_2	6.6	10^{-4}
Zincite	ZnO	a 8.2, c 11	10^{-4}-10^{-3}
Mullite	$3Al_2O_32SiO_2$	7	10^{-4}-10^{-3}
Olivine	$(Mg, Fe)_2[SiO_4]$	a 7.2, b 7.6, c 7.0	10^{-3}
Arizona ruby	$Mg_3Al_2[SiO_4]_3$	11	10^{-3}
Polar minerals			
Topaz	$Al_2[SiO_4](F, OH)_2$	a 6.8, b 6.8, c 6.5	10^{-2}-10^{-3}
Tourmaline	B-aluminosilicate	a 6.3, c 7.1	10^{-3}
Talcum	$Mg_3[Si_4O_{10}](OH)_2$	5	10^{-2}
Asbestos	$Mg_6[Si_4O_{10}](OH)_8$	3.1	10^{-2}
Serpentine	$Mg_6[Si_4O_{10}](OH)_8$	6.1	10^{-2}
Muscovite	$KAl_2[AlSi_3O_{10}]OH$	a 13, c 7	a 0.2, c 10^{-4}
Phlogopite	$KMg_3[AlSi_3O_{10}]OH$	a 30, c 6	a 0.3, c 10^{-3}
Orthoclase	$K[AlSi_3O_8]$	7	10^{-3} - 0.05
Hornblende	Na, Ca, Mg, Fe-aljumosilikat	5	10^{-2}

Table 1. The dielectric characteristics of minerals with small dissipation factor.

The values of ε and tgδ rocks are determined by existing mechanisms of polarization. Most crystals have electronic polarization. The crystals, with only e-polarization (with covalent bonds), have little ε (2.0-3.0, and the biggest - 5.7 - diamond) and very low tgδ order 10^{-4}. In crystals with ionic bonds an additional contribution to ε is made the ionic polarization. Therefore, the dielectric constant is higher: halite - 5.9, fluorite - 6.7, etc. Dielectric loss of these nonpolar mineral remain small until IR range, where the resonance begins variance.

In polar dielectrics there are permanent dipoles. They are capable of reorientation, giving an additional contribution to ε' and losses. The average time of reorientation is usually in the range of 10^{-3}-10^{-9} s. At frequencies of 10^3 - 10^9 Hz are observed relaxation dispersion and maximum of dielectric losses, because the dipoles do not have time to shift between the electric field. Polar minerals have higher losses and their tgδ usually in the range of 10^{-3}-10^{-2}.

The dielectric properties of some materials are presented in (Petrov a, 2002). In Table 1. presents data on the dielectric parameters of polar and nonpolar minerals. Due to lack of data for some polar dielectric characteristics of minerals are presented in the radio frequency range. Power dissipation of the electromagnetic microwave field in dielectrics is directly proportional to the dielectric constant and dielectric loss tangent. Measuring of dielectric characteristics is attracting the considerable interest for specialists.

Mineral	Composition	γ, 1/(Ohm·m)
Gold	Au	$4.4 \cdot 10^7$
Graphite crystalline	C	a 10^4, c $2.5 \cdot 10^6$
Cuprite	Cu_2O	1-10
Calcocite	Cu_2S	10-30
Covellite	CuS	10^2-10^6
Calcopirite	$CuFeS_2$	10^2-10^5
Haematite	Fe_2O_3	10-10^2
Magnetite	Fe_3O_4	10-10^2
Titaniferous magnetite	$(Fe, Ti)_2O_3$	0.1-1
Chromite	$FeCr_2O_4$	> 1
Cassiterite	SnO_2	10-10^3
Uraninite	UO_2	> 1
Pyrite	FeS_2	10-10^5
Marcasite	FeS_2	10-10^2
Pentlandite	$(Fe, Ni)_9S_8$	> 1
Molibdenite	MoS_2	10-10^3
Blende	ZnS	10^{-5}-10
Galenite	PbS	10^3-10^5
Arsenopirite	FeAsS	0.1-1
Tennantite	$Cu_3 (Sh, As) S_2$	> 1
Nickelite	NiAs	10^5-10^6
Ilmenite	$FeTiO_3$	1-10
Polianite	MgO_2	0,1-1
Manganite	MgO (OH)	> 1
Tantalite	$(Fe, Mn) (Nb, Ta)_2O_6$	> 1

Table 2. Conductance of ore minerals.

In conductive substances significant contribution to the dielectric loss makes their electrical conductivity. The depth δ in such substances is less than a millimetre. Therefore, power dissipation of the electromagnetic field in such minerals is directly proportional to the conductivity. The conductivities of some minerals are given in Table 2.

In reality, the rocks have a complex structure and dielectric parameters are determined by different mechanisms of losses - relaxation and conduction. The majority of rocks are minerals with high losses. It is well known that the loss of conductivity in semiconducting materials greatly increase with increasing temperature, as well as with increasing humidity. In anisotropic crystals the values of ε depend on crystallographic direction. In tables permittivities indicate along different axes. Dielectric characteristics also depend on impurities.

In porous rocks the conductivity, dielectric constant and dissipation factor increase with increasing humidity. This dependence is because of increase of water content in the pores. Water have great values of ε=80 and $tg\delta$=0.21 on 3.0 GHz. In addition, water is a good solvent salt, which leads to an increase in dielectric loss. This relationship is particularly well observed in the study of the dielectric characteristics of kimberlites (Didenko en al., 2008).

Many rocks are heterogeneous materials containing conducting inclusions. Conductivity of inclusion leads to the migration of the dielectric losses. The dissipation factor becomes dependent on frequency. Typically, the maximum migration losses lie in the low frequencies. In the ores with strongly conductive minerals maximum of dissipation factor is in meter or decimetres range. Contribution migration mechanism is proportional to the content of conductive inclusions.

Substance	Composition	ε (on axes a, b, c)	tgδ
Calcite	$CaCO_3$	8	10^{-2}
Magnesite	$MgCO_3$	10.6	10^{-2} - 10^{-3}
Dolomite	$CaMg(CO_3)_2$	7.7	10^{-2}
Siderite	$FeCO_3$	7	10^{-2}
Cerussite	$PbCO_3$	23	10^{-1}-10^{-2}
Strontianite	$SrCO_3$	7	10^{-2} - 10^{-3}
Anglesite	$PbSO_4$	14	10^{-2}
Gypsum	$CaSO_4 2H_2O$	7.9	10^{-2}
Diaspore	$HAlO_2$	6.2	10^{-2}
Goethite	$HFeO_2$	12	0.1
Limonite	$Fe_2O_3nH_2O$	32	0.1
Jacobsite	$MnFe_2O_4$	15	0.1
Scheelite	$CaWO_4$	a 11, c 9.5	0.1
Powellite	$CaMoO_4$	a 24, c 20	10^{-2}
Wulfenite	$PbMoO_4$	a 30, c 40	0.1
Crocoite	$PbCrO_4$	9.6	0.1
Proustite	Ag_3AsS_3	30	0.1 - 1
Pyrargyrite	Ag_3SbS_3	20	1

Table 3. The dielectric characteristics of minerals with high dissipation factor.

It should be noted that the majority of rocks in the microwave range are dielectrics with losses. The dielectric characteristics of minerals with high losses are presented in Table 3. Characteristics of minerals depend on exterior requirements and deposits. In each specific case it is necessary to measure dielectric characteristics. All data for the tables have been taken from (Petrov b, 2002). These data can be used only for preliminary assessments of the process.

To study the emolliating and fracture of rocks under the influence of electromagnetic microwave field, to determine the effectiveness and to describe processes it is necessary to measure the dielectric characteristics of rock in ranges of frequency and temperature. The information obtained will allow to optimize a processing of ores and maximize energy efficiency, when most of microwave energy is absorbed by the ores.

There are waveguide and resonator methods of measurement of dielectric characteristics, which can be used to measure substances with high dissipation factor. All these methods have their advantages and disadvantages. Which one to choose depends on your hardware and tools, experience and preferences of the researcher. In (Petrov, 1979) and (Petrov a, 2002) for the dielectric characteristics measurement of ore with very high dielectric losses (tgδ ≈ 0.2-1.0) is proposed to use the coaxial waveguide method for measuring line. The advantage of the method is the ability to measure the characteristics in the frequency range 1 GHz on the same equipment.

In the study of fracture processes of kimberlites by superprompt microwave heating (Didenko en al., 2008) preference to resonance method presented in (Esaulkov en al., 2008) was given. Resonance method for measuring the complex dielectric constant, despite the different character of its technical realization, is to study the resonance curves before and after addition of a dielectric in an oscillating circuit. Method allows to determine the real and imaginary parts of permittivity of the dielectric by measuring Q-factor of the circuit and its resonant frequency. The value of ε is determined experimentally from the difference frequency ($f_0 - f_\varepsilon$). Dependence tgδ from (Q_0, Q_ε) - much more difficult. The real part of complex permittivity is measured more precisely than imaginary. As one of the resonance methods for measuring permittivity of arbitrary shape samples is designed probe method of comparison. The method is based on comparison of resonance frequency bias in the standard resonator with investigated dielectric sample of permittivity ε and identical shape sample of precisely known permittivity ε_p. The method is useful for measuring substance permittivity with different dissipation factor. The modern numerical methods of resonator calculation can also be applied in this method.

Dielectric behaviours of kimberlites were measured by this method using cylindrical cavity with oscillations such as TM010 at resonator frequency 2.8 GHz. Cylindrical discs of plexiglas (ε=2.57; tgδ=0.001), teflon (ε=2.1; tgδ=0.0001) and ebony (ε=2.8 и tgδ=0.007) were used as reference with known characteristics. The kimberlites (ksenotufobrekchy, porphyritic kimberlite, kimberlite breccia autolithic) were investigated at relative humidity of muck from 1 to 8 %. Cylindrical samples (volume 0.2 cm^3) axisymmetric placed in the cavity and electrodynamics characteristics of it were measured. The same were made with standard samples having the same shape and size. Processing the results of measurements were performed using the analytical expressions given in (Didenko en al., 2008) and using numerical methods implemented in the existing software package (Esaulkov en al., 2008). The measurement accuracy of permittivity was 5%, and dissipation factor - 10%. Dielectric characteristics of kimberlites of different types differ in one and half times and they are highly dependent on relative humidity breeds. Averaging of observed data is executed. Kimberlites with a relative humidity of less than 1% is ε=6.5 and tgδ=0.15. Kimberlites with relative humidity of more than 4% - ε=12 and tgδ=0.25.

Thus, knowledge of the dielectric characteristics of rocks will allow to identify the basic mechanisms of its emolliating and destruction, to assess the efficiency of this process and to implement development and optimization of equipment for the processing of rock.

3. Physical principles of rocks distraction

For today there is not comprehensive description of processes of emolliating and fracture of rocks under the influence of microwave electromagnetic fields. Description of the processes of emolliating and fracture of rocks lying at the intersection of sciences as microwave electronics, thermal engineering, geophysics, solid state physics, plasma physics, chemistry. In (Emelin, 1990), (Nekrasov, 1979), (Didenko, 2003), (Petrov a, 2002), (Walkiewicz en al., 1991) and (Michal et al., 2010) are attempted to describe the fracture processes at non-uniform microwave heating. It is assumed that there are two mechanisms of crack formation and fracture of rocks - heat and the discharge. The thermal mechanism is predominant in the processes of destruction and emolliating rocks, as this requires less strength of electromagnetic fields. In experimental investigations discharge mechanism of failure is more difficult to isolate and describe. Only in some cases, it is possible to assume its presence. Thermal mechanism of rocks destruction at non-uniform microwave heating is more brightly allocated. It depends on the type of rock, structure and chemical composition. Cracking and fracture of rocks due to heat of the microwave energy can occur for two reasons:

- Due to the linear expansion of solids, when the stresses K exceed the breaking stress: $\alpha\Delta T=K/E$, where α - coefficient of linear expansion, ΔT - temperature change during heating and E - Young's modulus. In fact, fracture stress depends more complicated from Young's modulus. The rocks are the brecciated structure consisting of clusters. The clusters have different dielectric characteristics and different coefficients of linear expansion. The non-homogeneous microwave heating of the clusters leads to non-uniform tension and thermomechanical stresses arise. The destruction of such a mechanism occurs at the boundaries of clusters.
- Due to the rapid evaporation of water contained in rocks pores and microcracks when the vapor pressures inside the water-filled cavities exceed the breaking stress. Some rocks have micropores that could contain water. The relative humidity of rocks can reach 15%.

At normal thermal heating of rocks also occur thermomechanical stresses. There are a process of evaporation of moisture, decrepitation, a relaxation of residual stresses, polymorphous and phase transitions burning off of organic compounds (Emelin, (1990). The reducing of rocks strength with increasing temperature shows in Fig. 1. Conventional heating is slow heating by thermal conductivity from surface of rock.

Let us consider the mechanism of thermomechanical stresses in rock under microwave exposure. At the expense of dielectric losses there is a volume heating of rock. The increment of rocks temperature is

$$\Delta T=(P\cdot t)/(c\cdot\rho), \tag{2}$$

where P - microwave power absorbed per unit volume of rock; t - exposure time of the field, c - heat capacity, ρ - soil density.

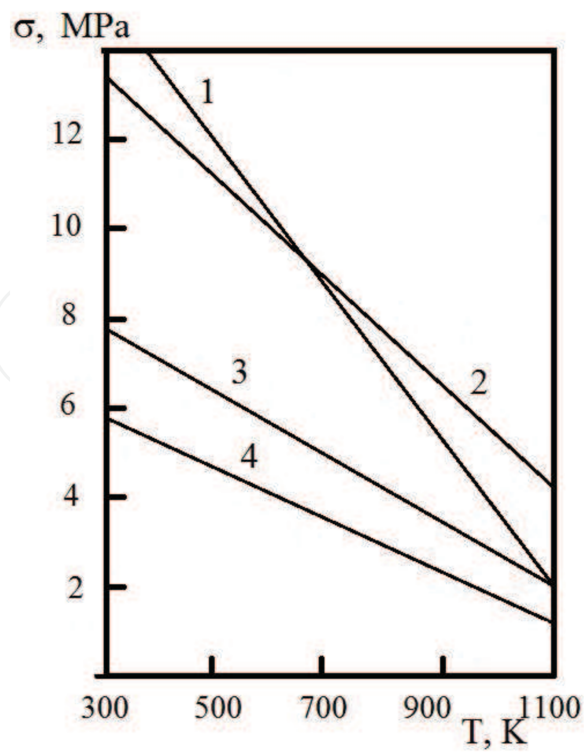

Fig. 1. Dependence of ultimate strength on extension from temperature for samples of ferruginous quartzite (1), gneiss (2), harburgite (3) and dolerite (4).

In (Petrov a, 2002) proposed to place minerals at the time 100 microseconds in the microwave field with frequency 2.45 GHz and strength of 1 MV/m (that is close to brake down limit for air). The heating of different types minerals are following:
quartz, halite, etc. non-polar dielectrics - $\Delta T = 0.005$ K;
felspars, asbestos, etc. polar dielectrics - $\Delta T = 0.5$ K;
goethite, limonite, etc. semiconducting soils - ΔT more than 5 K;
pyrite, hematite, magnetite, etc. conductive soils - ΔT more than 500 K.
Consequently, conducting and semiconducting minerals considerably heat up in the microwave electric field, whereas the dielectric minerals are feebly heated. To heat insulator dielectrics can use higher frequencies, but this prevents decrease in the penetration depth δ of the microwave field. Increasing the radiating time or microwave power leads to significant volumetrical heating of rocks. A significant increasing of radiating time t leads to significant increase in power consumption for rocks emolliating. In the case of loss strength and destruction of the microwave heating tend to prompt heating (temperature excursion) of rocks. The thermomechanical stresses at the temperature excursion exceed the fracture stress. Only in this case, the required energy consumption for heating rocks is decreased.
Let's estimate the energy efficiency of emolliating. To increase the temperature of rock mass m at ΔT needs the energy $W=m \cdot c \cdot \Delta T$. The typical heat capacity of minerals is 700-800 J/(kg·K). To heat soil ton on 100 degrees 75 MJ (20 kW·hour) energy is required. Total energy efficiency (efficiency of microwave generator and absorption factor) is amount to about 30 kWh per ton of rock, which is comparable to energy consumption at purely mechanical crushing.
Microwave technology of emolliating is energetically favorable for rocks containing small amount (up to 10%) of ore (semiconducting or conducting) minerals. Microwave energy

heats only the mineral without heating the dielectric mineral tailings. In this case, lose of emolliating is spent no more than 3 kW·h/ton and subsequent operations of crushing and dressing saved - 10-30 kW·h/ton. Consider this process in more detail. Treated rock contains minerals of metals (pyrite, nickel, manganite, etc.) and waste rock (quartz, calcite, granite, etc.). The first minerals have major losses over microwave range, and second - rather small. Therefore, in the microwave field ore minerals are heated, and the waste remains in the beginning cold. The temperature is equalized only after a while. To determine the temperature distribution near the phase boundary it is necessary to solve the dynamic heat equation for two-phase mediums media. The solution displays that the temperature distribution is described by an error integral with a diffusion length:

$$L=2\cdot(\lambda_{cond}\cdot t/(c\cdot\rho))^{0.5}, \quad (3)$$

where λ_{cond} - coefficient of thermal conductivity. If phase 1 absorbs microwave energy, and phase 2 is not, then the diffusion length L characterizes the distance to which the heat from the phase 1 is distributed in the phase 2 at time t. The qualitative picture of temperature distribution in the two-phase medium with flat phase boundaries is displayed in Fig. 2.

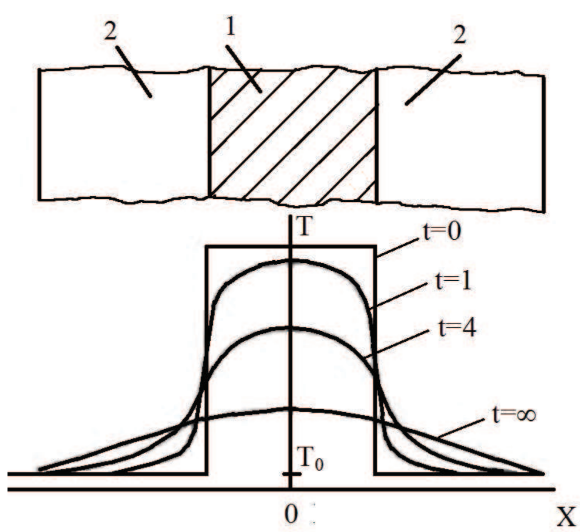

Fig. 2. Temperature allocation in a plate consisting from interior absorbent phase 1 and an outdoor non absorbent phase 2, at instantaneous (t = 0 ms), pulsing (t = 1 ms and 4 ms) and static (t =∞) microwave heating.

For instant heating of phase 1 of the pulse duration t = 0 high temperature is only created in this phase, in phase 2 it is equal to the ambient temperature T_0. In the static case the temperature is aligned on both phases. The distribution of temperature near the border is sharply inhomogeneous at pulsed heating. The temperature gradient increases with decreasing pulse duration.

Substituting (3) the typical numerical values of minerals, we get $L = (10^{-5}\cdot t)^{0.5}$. Consequently, during the 100 ms heat has time to be spread for 1 mm from phase boundary, for 1 ms at 0.1 mm and for 10 microseconds at 10 microns. To reduce heat losses in the waste minerals it is necessary to do the heating time of ore mineral whenever possible small - no more than 1 ms. It is possible only when using a microwave generators with major pulsing power.

The temperature drop at phase boundary under pulsed microwave heating leads to significant thermomechanical stresses caused by differential thermal expansion. Numerical calculation of mechanical stresses in calcite with pyrite inclusions (balls of diameter 0.15 mm) heated by pulses of microwave fields of different duration is presented in (Gridin & Goncharov, 2009). The calculation was made by finite element method and its results are presented in Fig. 3. Mechanical stresses in pyrite are compressive and it has a negative sign. Mechanical stresses in calcite are stretching and it has a positive sign. The temperature have time to equalize the volume when the heating time 1 s (curves 1; Fig. 3.). Emerging thermomechanical stresses are small (in calcite, a maximum of 20 MPa). After irradiation for 40 ms heat is also greatly distributed over both phases. The mechanical stress have maximum of 30 MPa (curves 2; Fig. 3.). In the case of prompt microwave heating (40 microseconds, curves 3; Fig. 3.) the temperature gradient between the phases increase up to 1200 K, and mechanical stress - 360 MPa. At the same time energy consumption at microsecond pulses is of an order of magnitude smaller than the millisecond pulses. This confirms the advantages of prompt heating by high microwave power.

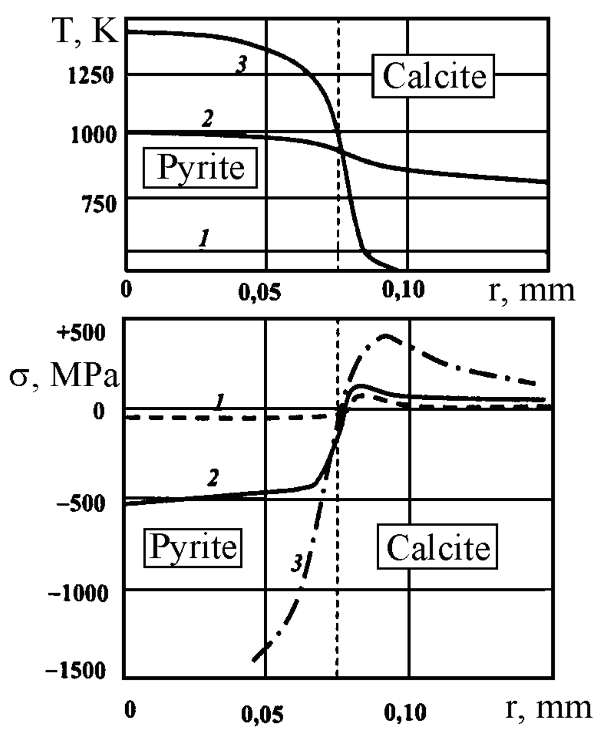

Fig. 3. The radial allocation of temperature T and thermomechanical stress σ the sample of calcite with focus globe turning on of pyrite at microwave heating: **1** - power density of 10^{10} W/m^3, duration t=1 s; **2** - power of 10^{12} W/m^3, t=40 ms; **3** - 10^{14} W/m^3, t=0.04 ms.

Obtained in the calculation of thermomechanical stresses in calcite (20, 30 and 360 MPa) is certainly more than the ultimate strength of rock, (5-15 MPa for granite; 3.5-5.5 MPa for limestone; 2.1-6.9 MPa for sandstone). Therefore, calcite will be cracking around pyrite inclusions. This effect should facilitate and reduce the price of the subsequent grinding and separation.

Consider other mechanism of emolliating and fracture of porous rocks. In such rocks the mechanism of failure due to saturated vapor pressure of water in the rocks pores is predominant. The porosity of rocks ranges from 1 to 15% by volume. The dependences of the dielectric characteristics of porous rocks from its moisture are presented in Table 4. The moisture increase leads to permittivity increase and losses increase in rocks.

Rock	Porosity, %	Permittivity		Resistivity, Ohm	
		Dry	Wet	Dry	Wet
Sandstone	14	5	10	10^4	10^3
Clay slate	20	5	20	10^4	10^3
Granite	2.8	6	7	10^6	10^4
Marble	3	7	8	$3{\cdot}10^8$	10^6
Basalt	4	18		$3{\cdot}10^4$	$2{\cdot}10^3$
Porphyry	3.2			$2{\cdot}10^7$	$3{\cdot}10^3$
Diabase	1.4	8.5		10^3	$6{\cdot}10^4$
Chalkstone	To 20	8	12	10^2	10

Table 4. Change of the dielectric characteristics of porous mucks at moistening.

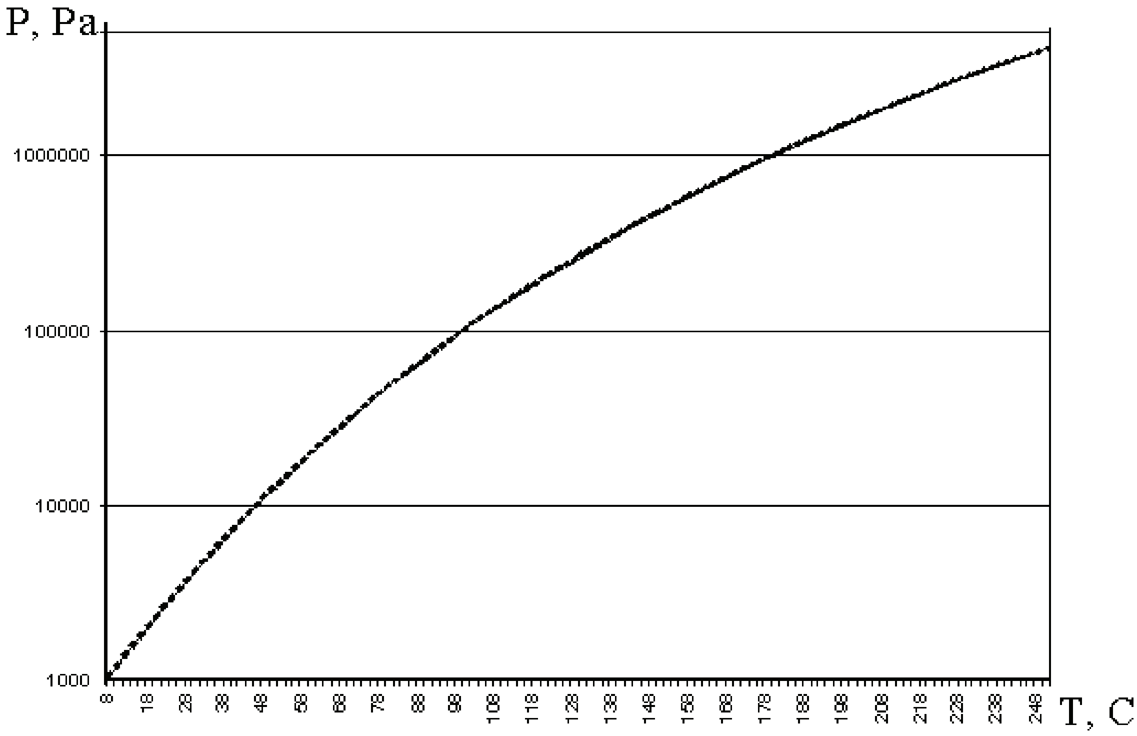

Fig. 4. The pressure of water saturated steams on temperature.

To develop a rigorous theoretical description of rocks destruction due to water pressure in the micropores it is represented the difficult physical and mathematical problem. Therefore, based on empirical data it is possible only to estimate rock fracture processes. Dependence of saturated steams pressure of water on its temperature is given on Fig. 4. Thus, at rock temperature of 100 °C vapour pressure in pores will be 10^5 Pa, and at 200 °C - $2{\cdot}10^6$ Pa. In fact, water temperature and pressure in rocks pores will be much greater because water in pores will better absorb microwave energy than dielectric rocks minerals. To assess the energy efficiency of the rock destruction is required to determine the temperature of beginning of rock destruction. It is necessary to mean for many rocks that the tension fracture stress is less than compression. Thus, vapour pressure 2 MPa may be sufficient to destroy rock. In the experiments (Didenko en al., 2005) and (Didenko en al., 2008) noted that with increasing heating rate the efficiency of destruction increases also. This means that

stream has not time to percolate from pores on rocks surface and pressure in pores does not collapse. For some rocks, for example kimberlite, such mechanism of emolliating and fracture will be predominating.
Short pulses of microwave field duration of 10 ns - 1 microsecond with power of 10 MW - 10 GW can also be used to rocks destruction. Energy of these pulses reduces to breakdowns of air gaps between electrodes and rocks pieces. Microwave energy is spent plasma heating of the microwave discharge. This causes formation of shock waves, which may lead to the destruction of portions of rocks. Such experiments on destruction of surface coatings of metals are described in (Novik & Zilbershmitt, 1996). This indicates the possibility of using microwave discharges for destruction of rocks. In some cases the discharge mechanism of fracture can appear more favourable energy, than thermal.
Thus, processes of emolliating and fracture of rocks in microwave electromagnetic field are determined.

4. The equipment for rocks destruction

Establish of effective equipment for emolliating and fracture of rocks is complicated, but completely realized the problem. The technologies of microwave processing of various materials have already been worked out. They are applied in industry (vulcanization of rubber, sintering of ceramics, wood drying, the synthesis of new materials, etc.), agriculture (disinfection of grain) and just at home (microwave ovens). The methods and the approaches for creating energy-efficient systems that meet the requirements for electromagnetic compatibility are already developed (Didenko, 2003), (Arkhangelsiy, 1998). In mining there are the features associated with large tonnage, severe conditions of equipment requirements, minimum energy consumption and major life equipment expectancy. The cyclic duty is not comprehensible to the industrial equipment. Loading and unloading operations of processed material reduce productivity. Industrial equipment requires a continuous operating mode. At designing the installations it is required to consider matching condition for the microwave generator working at chamber with rock. The mismatch of the generator with working chamber leads to significant energy losses, failure of operation and even failure of high-power microwave generators.
Dielectric parameters of rocks are changed at heating up. In some minerals the changes of phase or chemical transformations are observed at heating that also modifies their dielectric properties. In the dump rocks at microwave heating there are moisture reduction and decrease of permittivity and losses. Any changes at the rock dielectric parameters at microwave heating change the working camera input impedance that leads to mismatch of microwave line and microwave generator. To ensure constant coordination of microwave generator is necessary to use continuous mode of rocks loading into the chamber at constant speed. Such mode regime can be achieved by continuously spilling out rock through the working chamber with constant speed. In this case, the input impedance of working camera will be determined by average parameters of cold soil on its inlet and hot on an exit. Average input impedance of working camera will not change during processing and the generator will always work mode of maximum power.
At emolliating and fracture of rock choose appropriate types of installations: radiation type for processing of rock massif before the mechanical destruction and spilling type for irradiating of rock before mechanical grinding. The system of antennas creating high microwave power flux density in the rock is applied at radiation type. Rocks is been

transporting across the active zone of working chamber in installation of spilling type. Rock is heated in active zone.
From the point of view of efficiency it is desirable that microwave generator operated in continuous mode, but created an impulse heating on piece of rock. It can be achieved in the working chamber spilling type, when pieces of pre-crushing rocks wake up in the active zone of the working chamber. If the pieces of rock fall from height h and holding path in active zone is l, the action time is determined by the relation:

$$t=l/(2 \cdot g \cdot h)^{0.5}, \tag{4}$$

where g - a free fall acceleration, l <<h. So, at l = 15 mm and h = 3 m processing time is only 2 milliseconds. Approximate parameters of such working cabinets of spilling type are presented in the patent (Kingman, 2002). To increase the action time of the rock in working chamber in the active zone set a dielectric pipe with small losses at certain angle to the horizon. The moving pieces of rock are transported in pipe. Transporting speed of rock is determined by angle of inclination of pipe and rock friction coefficient about pipe wall.
In developing the working chambers of emolliating and fracture of rocks it is necessary to have maximum transfer efficiency of microwave power to heating rock. The loss power in dielectric P_d fractionally or completely filling the working chamber is recorded

$$P_d = \frac{\sigma}{2} \int_{V_d} \left|\vec{E}_d\right|^2 dV = \omega_0 \varepsilon' tg\delta \int_{V_d} \left|\vec{E}_d\right|^2 dV , \tag{5}$$

where - V_d volume of dielectric; $\varepsilon'=\varepsilon\varepsilon_0$ - permittivity of dielectric; tgδ - dissipation factor and E_d electric intensity in a dielectric. Therefore for magnification of transfer efficiency of microwave power the heated rock it is necessary to increase an electric intensity in rock or to make maximum filling of working chamber.
Technological installation for emolliating and fracture of rocks (Fig. 5.) consists of a transmission line, a powerful generator and a working chamber with spilling system of continuous supply and shipment of rocks. Size of rock fragments is determined by the following criteria: necessity to maintain the ecological safety of microwave installation at acting spilling system, field penetration depth into rock should be comparable to size of rocks pieces, homogeneity of electric intensity in piece with its location at the maximum electric field. On frequency of 2.45 GHz the maximum size of pieces should not exceed 30 mm. Working chamber for destruction of rocks can be irradiating (Fig. 5.a), waveguide (Fig. 5.b) and resonator (Fig. 5.c). Design of these cameras should ensure maximum efficiency of microwave power transmission processed rock.

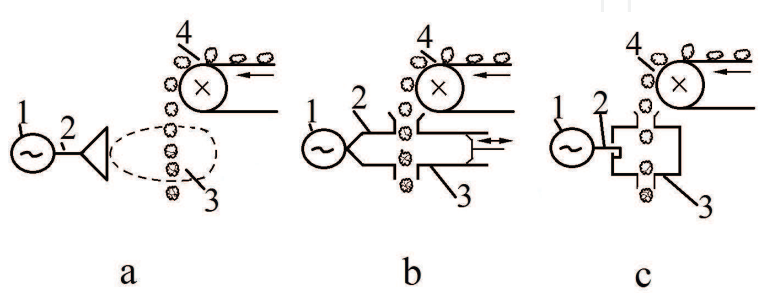

Fig. 5. Installations for processing rocks by microwave field: 1 - microwave generator; 2 - feeder; 3 - working chamber; 4 - spilling system.

Irradiating working chambers represent a system of antenna radiators matching with microwave line. Irradiating working chambers can be used both for processing of rock before its extraction and for loss of strength and fracture in spilling mode. In this chamber the stream of rock impinging in free space is irradiated by an antenna, such as horn (Fig. 5.a). Such a simple design of the installation requires the difficult protection against microwave radiation. In such working chamber it is possible to irradiate uniformly materials. It is impossible to get big efficiency of microwave power transmission to rock because of power losses in the space.

Waveguide working chambers operate in traveling wave mode. Waveguide working chambers is sufficiently broadband. They may be in the form of waveguide inserts and matched loads. The matched loads efficiency of microwave power transmission to rocks can reach 80% at wide range. Matched loads (Fig. 5.b) can use different waveguides working on dominant mode and active zone is placed in the maximum electric field. Matched loads work with large loss dielectrics and can have a system of adjustment of waveguide pistons.

For effective heating of samples of small volumes with low dielectric losses it is preferable to use resonator working chamber.

Resonator chambers provide high electric intensity for installed microwave power (Fig. 5.c). They should be used to influence the small pieces of rock with low dielectric losses. In the resonator chambers transfer coefficient of microwave energy to rock may reach 85-90%. Resonators are singlemode and multimode. Multimode cavities with introduction of processed material begin to work on new oscillations mode with self-resonant frequencies close to the frequency of microwave generator. Unfortunately, in these cavities can be observed unevenness of microwave heating of rocks and transfer coefficient of microwave energy to rock does not exceed 70%. However, resonator working chambers are the most promising for microwave heating for emolliating and fracture of rocks.

Waveguide and resonator working chambers can be made on the basis of rectangular and circular waveguides, strip line and coaxial transmission lines, unclosed and enclosed slowing structures. Using modern software packages numerical simulation of microwave devices, it is possible to develop working chamber of any construction. Installations for microwave heating for emolliating and fracture of rocks also include matching and trimmer microwave units, security features microwave components from the destructive and polluting effects of the rock and protection from microwave radiation. Microwave field shielding in places loading and unloading rocks is carried out with the help of below-cutoff waveguides and throttle elements.

Thus, at the present stage of development of microwave electronics it is possible to create effective systems for rocks destruction.

5. Application of microwave heating for emolliating and fracture

The application of microwave energy for emolliating and fracture of rocks is considered. The major cycle of research on microwave energy use has been executed in Russia. In other countries also carried out work on the loss of rocks strength. Great attention was always paid to the questions of mineral extraction and raw dressing. In this chapter will describe the experimental research results of microwave action for thawing of frozen soils, emolliating of various ores, extraction of hard gold, a dispersion of hard coals and fracture of kimberlites.

Great volume of research on microwave energy application to the emolliating of frozen soils is executed in Russia. The essence of a problem consists that strength of frozen soils is very high and increases with decreasing temperature. At dynamic loads and temperature of minus 30°C the compressive strength of frozen sand attains 15 MPa, and frozen clay - 75 MPa which is higher than that of many rocks and minerals. Therefore mining of the frozen soils in a winter time and the permafrost usual excavation technics is possible only with prior thawing. The microwave heating for loss of frozen soils strength is actual.

Works in this direction were intensively until 1990 (Nekrasov, 1979) and (Riabec, 1991). The complex for emolliating of the frozen soil during the digging of trenches and the installation for the wells expansion in the rocks have been created at the Leningrad Mining Institute (Russia). The complex consists of microwave installation and the earth-moving machine. The depth of mining for one pass is 0.3-0.5 m at power inputs of 5-6 kW·hour/m^3. Microwave equipment has microwave power of 50 kW at a frequency of 915 MHz. The installation for the wells expansion in the rocks emolliates by well directed stream of the microwave field and breaks rocks by cutting tool. Performances of installation as follows: the frequency of 2.45 MHz, microwave power 5 kW; diameter hole 800 mm; productivity of 4-10 m/hour depending on the a ground.

The study of dielectric characteristics of frozen soils depending on microwave frequency and the development of installations for emolliating were occupied in Yakutsk Scientific Centre (Russia). It was showed advantage of switching to the frequency of 430 MHz for frozen soils. The microwave installation for layering sinking pits in the frozen soil with depth to 1 m, power consumption of 30 kW·hour/m^3 and productivity 0.85 m^3/hour have been created. Comparison of microwave thawing and emolliating of frozen soils indicates advantages in operating velocity.

Let's execute survey of research on the microwave destruction of rock. In the patent (Maksimenko et al., 1977) is proposed an original method of rock destruction by irradiation of two microwave generators of Fig. 6. At first a rock massif 3 is irradiated with small microwave density (150-300 W/cm^2) from the generator 1 to the formation of the heat trace. Then in a perpendicular direction the massif is irradiated waves of higher density (300-5000 W/cm^2) from the generator 2. The first generator creates in the rock heated zone 4 with

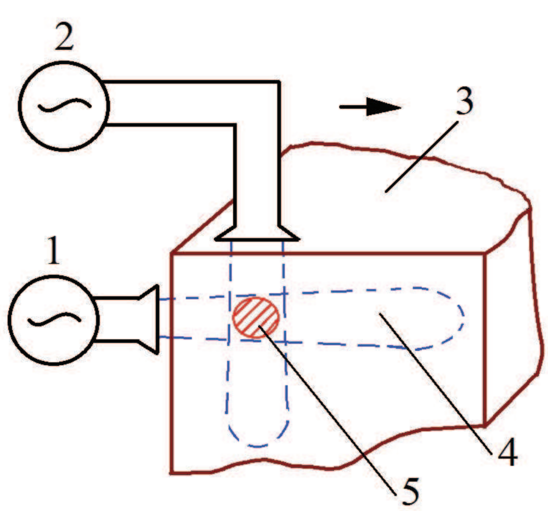

Fig. 6. The advantageous process of making emolliating channels in rocks with two microwave generators.

increased dissipation factor. Microwave power from generator 2 is absorbed mainly in the area of intersection of irradiation 5. The rapid heating zones 5 leads to thermal expansion, phase transitions and the formation of gas phase in this area, which leads to the destruction of rocks. Translocating the antennas it is possible to create the channel of broken rocks. Crystalline shale, granites, sandstones and other rooks were destroyed with use of generators at frequency of 2.45 GHz.

Similar theoretical and experimental researches for sandstone fracture were studied in (Obrazcov, 1976) and (Krasnovskij & Uvarov, 1991). At irradiation density of 300 W/cm^2 the destruction occurs in the form of periodic separation husks thickness of 2-4 cm. The husks thickness is decrease and the fracture frequency is increase then the density of power flux was increased. Explosive fracture of strong sandstones with damp from 0.1 to 2 % volume was observed at densities of 1000-3000 W/cm^2. Damp essentially influences both the energy intensity of explosive destruction and the critical density of microwave power. Explosive fracture of various sandstones by a microwave field is studied at the radiant density of 500 W/cm^2 from the generator by power of 50 kW. The slot by depth 5-20 cm is generated at beam translocating travel in block sandstone. Power consumption amounted to 80-200 kW·hour/m^3. Fracture of strong sandstones at radiation by millimeter waves (3.5 mm) with densities of pulsing energy to 40 kW/cm^2 and pulse duration of 30 ms is featured in (Krasnovskij & Uvarov, 1991). Power consumption of fracture process at major densities is 240-250 J/cm^3, whereas at smaller (a few kW/cm^2) - 360-700 J/cm^3. Hence, the adiabatic regime of a heating a high power allows to reduce power consumption of microwave destruction essentially. The density of microwave field in 20-40 kW/cm^2 produces the surface electric breakdown of the irradiated rock. In (Krasnovskij & Uvarov, 1991) the possibility of practical use combined plasma-wave destruction is viewed.

Comprehensive theoretical and experimental investigations of emolliating by electromagnetic fields conducted in Moscow Mining Institute (Russia) (Gridin & Goncharov, 2009). Samples of iron ore (about 45% magnetite, 10% hematite and 45% quartz) with dimensions 15×15×30 mm had been irradiated from the generator with power 0.5 kW at frequency 2.45 GHz. Their flour milling and dressing were studied. Because of small microwave power heating up of the sample was slow - to 200°C for 50 seconds with, 450 °C for 3 mines and to 900 °C for 10 minutes. At a heating to a redness explosive fracture was observed. The scraps which boundary transited on mining stratums separated from samples. Such fracture is caused by presence in iron ore of abound water and its evaporation. At the cooling of the heated samples in water the cracking was faster and often leads to their destruction. According to the made calculations the temperature increase at one degree leads to thermomechanical stresses to the magnetite grains - tensile 0.17-0.23 MPa, the hematite grains - tensile 0.35-0.40 MPa and the quartz grains - compressive 0.21-0.27 MPa. At temperature spring on 100 degrees thermomechanical stresses should exceed ultimate strength of minerals. The appearance of cracks coming mainly along the grain boundaries is confirmed by structural studies of processed ore. The flour milling and mesh analysis of the samples processed by the microwave heating testifies to loss of ore strength and reducing of power consumption. Dressing of samples by magnetic separation in a strong magnetic field is found to improve the quality concentrate in comparison with raw ore. The yield of concentrate increases at 11.6%. The greatest effect is achieved on the samples heated to 200 °C, instead of to 900 °C. Researches (Kondrashov & Moskalev, 1971) and (Chelyshkina & Korobsky, 1988) have convincingly proved necessity of selection of an optimum regime of microwave processing for each rocks type.

Researches on the emolliating and destruction of rock are carried out in countries where there is a developed mineral industry. In (Lindroth en al., 1991) was patented a method for removing the formation of solid rock with strength of 170 MPa by microwave irradiating rocks in front of the cutting tool. As a result of thermomechanical stresses in the rock formation of microcracks and discontinuities. That leads to the decrease of fracture energy consumption.

In the patent (Tranquilla, 1998) company EMR Microwave Technology Corporation is proposed to process the ore or concentrate by spilling through a rectangular microwave cavity in the maximum of electric intensity. Preferable parameters of generator are power 10-50 kW and frequency of 915 MHz or 2.45 GHz. The resonator Q-factor should be within 1000-25000. With these parameters the processing time is no more than 6 seconds.

In (Walkiewicz en. al 1991). the flour milling of iron ore after processing in microwave field was explored. Samples of ore sizes of 3 cm contained hematite, magnetite and goethite. The generator with power of 3 kW and frequency of 2.45 GHz heated them up to temperature 940 °C. By means of a scanning electronic microscope the change of microscopic structure of samples at their processing was studied. The flour milling and screen analysis was made also. Microcracks at the grain boundaries are visible on a photomicrography of the processing samples. The research noted that energy consumption for heating is reduced with increasing power of the magnetron to 6 kW.

In research (Salsman et al., 1996) correctness of calculation of microwave heating of ores was mustered by experiment with the artificial composites containing a quartz and 1-7% chalcopyrite absorber. The composite heated up in microwave oven (1 kW) during 120 seconds. The energy analysis microwave loss of strength was presented. The thermomechanical stresses created in ore are 50 MPa (temperature jump at 200 degrees) if the processed ore contains 2.5% by weight of the absorbing minerals. Power consumption in pulsed mode of processing was only 0.8 kW·hour/t. Thus, processing of rocks for the purpose of a loss of strength by powerful microwave impulses allows to reduce power consumption.

One of problems that can be solved in the processing of the rock it is more effective dressing and extraction of minerals. In recent years, the world scientific community became interested in the problem of improving the gold extraction from the tailings of old minings.

However, the extraction of gold from the waste pile is problematic. In addition to the low percentage of gold content - (1-3 g/ton), it is difficult to extract. Gold corpuscles particles in this material have a size from hundredths to tenths of a micrometer and are concluded in other minerals (mainly pyrite and arsenopyrite). Therefore they are not extracted by a usual method at use of cyanides solutions. For extraction of this gold it is necessary to uncover or destroy shell of sulfides before cyanation. Current production technology is very energy intensive and not environmentally friendly. Using the thermomechanical stress at the prompt microwave heating and the microwave discharges it is possible to release dust grains of gold from sulfide shells. The sulfide shell which is absorbed microwave energy is rapid heated and cracked by the energy of microwave pulse. As a result metal becomes accessible to extraction by solutions. Microwave processing allows to raise degree of disclosure to increment extraction of precious metals, to use for their extraction poor rock. Besides, fine grinding of a concentrate to tens micrometers is not needed at microwave processing, there is enough sizes 0.5-2 mm.

Work to extraction of gold using microwave field has been begun in Canada (Haque, 1987). At a usual heating the concentrate starts to decompose at temperature 550 °C. At microwave heating that is at 420 °C. Extraction of gold and silver by cyanidation grows depending on microwave power. In fact, the complete extraction of gold (98%) occurs at powers of 5-6 kW. EMR Microwave Technology Corp. (Murray, 1998) was working on manufacturing equipment for microwave processing and optimization technology. It had been shown that microwave heating allows to reduce costs of preparing base ore to cyanation. Thus, the processing of 200 tons of concentrate per day by the microwave heating costs was $ 3.84 million, whereas the normal firing - $ 6.9 million.

In Russia has also carried out active research on the microwave energy application in the process of gold extraction (Lunin et al., 1997) and (Kolesnik et al., 2000). In the studies note that the microwave heating of raw auric concentrate causes the appearance of thermal stresses and the formation of intergranular microcracks. Extraction of gold from the concentrate by the scheme "microwave firing up to 360 °C - cyanation" was 94.8%, that on 8.3 % above in comparison with normal firing scheme.

In research (Chanturija et al., 1999) it is offered to process raw auric concentrate by the short electromagnetic impulses which spectrum covers the microwave range. In the same study display the prospects of nano-pulse radiation of raw auric concentrate. It is offered to explore agency of an electric intensity on formations of pin-holes of a disruption and on fractures of sulphidic shells.

In (Boriskov et al., 2000) presents experimental data on the irradiation of the tail concentrate by nanosecond pulses. It is shown that with increase in the number of pulses the degree of gold extraction grows at the subsequent cyanation. Thus, pulsed radiation also may be used for a loss of strength of rocks.

Research of applications microwave energy in mining industry carried out in National Research Nuclear University MEPhI (NRNU MEPhI) (Russia) (Didenko, 2003), (Didenko en al., 2005), (Didenko et al., 2008) and (Prokopenko & Zverev, 2008) Superprompt microwave heating was used to the fine destruction of coals and the fracture of kimberlites. It was showed that during rapid heating of coals up to 120 °C is emolliating and distraction of coal (Didenko, 2003). The mechanism of dispersion is based on the extremely prompt heating of water located in the pores of rocks. Heating occurs in single-mode resonator working chambers at a frequency of 2.45 GHz. At such process it is possible to gain coil corpuscles with a size 10 microns. Fracture goes on boundaries of clusters that give the chance to clean up ash-forming impurities from coil dust. Estimates show that by using the microwave generator 5 kW it is possible to disperse 100 kg of coal. Stripped of ashes and impurities of sulphur the coal dust is supposed to be used for making of solar oil analogues without chemical methods.

In NRNU MEPhI together with JST ALROSA (Russia) in 2006-2008 is executed extensive amount of studies the processes of kimberlites fracture and development of the equipment for analysis of these processes. Studies have shown the promise of this destruction method. Some research results are presented in (Didenko en al., 2005), (Didenko en al., 2008). and (Prokopenko & Zverev, 2008). In the next chapter the research results of kimberlite fracture by microwave energy will be presented in more detail.

6. Microwave heating for fracture of kimberlite

One of the main problems in the diamond-mining industry is preservation of rough diamonds extraction. Up to 20% of extracted natural diamonds have faults of facets gained as a result of extraction and dressing of kimberlite rocks. The faults obtained on the wet self-grinding mill significantly reduce the cost of rough diamonds. New methods of safety processing are demanded.

In 2006-2008 in NRNU MEPI supported by Joint Stock Company ALROSA made series of researches (Didenko en al., 2005) on the processes of kimberlites fracture. The purposes of this study were to determine the technological parameters of kimberlites fracture, assessing the applicability and effectiveness of the new method of fracture, development of theoretical bases for creating spilling type installations, experimental study of operation of manufactured installation and make recommendations.

Kimberlite is the magmatic ultrabasic brecciate rock representing a carbonate-serpentine rock with insignificant amounts olivine, pirosseno, granite, ilmenite, phlogopite, apatite, magnetite and other minerals. Kimberlite represents assemblage of various dielectrics: a carbonate-calcium, silicates and oxides of iron, aluminium, magnesium, chrome, titanium, etc. Bound water contains only in a phlogopite (about 10 %) and consequently does not influence fracture process as the phlogopite content is insignificant. The brecciate structure of kimberlites means presence in it of pores with free water.

Studies have displayed that the mechanism of kimberlites fracture mixed in which will dominate destruction due to overheating of water in the pores of the rock. The study of dielectric and thermal characteristics kimberlite rocks is executed. At examination the kimberlite of following types was used: ksenotufobrekchy, porphyritic kimberlite, kimberlite breccia autolithic. The question of water content of kimberlites should pay special attention. The separation procedure of kimberlite on conditionally "dry" and artificial "wet" is produced. The results of density change indicate rocks porosity. The "wet" kimberlite contains from 4 to 8 percent water. For a more complete investigation it is interesting to study the natural moisture of kimberlite extracted immediately from opencast.

The rock fracture mechanism due to the saturated steam in the rocks pores is predominant. The advantage of this destruction method for the "wet" rocks has been shown on numerous experiments. To develop the strict theoretical exposition of these processes it is represented the difficult physical and mathematical problem. Therefore, based on empirical data, it is possible to execute only qualitative assessment of the destruction processes. Knowing temperature of an initiation of a fracture (Fig. 4.) it is possible to determine the stresses of rocks destruction. To describe the processes kimberlites fracture it is required to determine the destruction temperature and the desired heating rate for effective destroy.

Dielectric characteristics of kimberlite were determined by the probe method of comparison presented above. The dielectric for average kimberlite characteristics are gained: the "dry" kimberlite (with a relative humidity of less than 1%) is $\varepsilon = 6.5$ and $tg\delta = 0.15$; "wet" kimberlite (with a relative humidity of more than 4%) - $\varepsilon = 12$ and $tg\delta = 0.25$. The measurements were made at a frequency of 2.8 GHz. Dielectric characteristics of kimberlite slightly dependent on frequency therefore on frequency of 2.45 MHz they remain practically without changes. To ensure uniformity of heating of kimberlite pieces size should be comparable to the penetration depth δ. At frequency of 2.45 GHz, according to (1), the penetration depth will be 10.2 cm in the "dry" piece and 4.5 cm in the "wet" kimberlite. Thus, fragments with an average size of 3 cm heat up almost microwave field and a large dissipation factor promotes significant losses in the rock.

To determine the energy characteristics of kimberlites fracture processes it is necessary to execute estimates of thermal rate of a prompt microwave heating. The heat exchange processes are important in determining the efficiency of kimberlites destruction. Microwave heating power of mass $\dot{m}_{kimb}$ per second from the initial temperature T_0 to a temperature of destruction T_d is defined by well-known relation

$$\eta_p P_g = P_{kimb} = \dot{m}_{kimb} \cdot C_k \cdot \left(T_d - T_0\right), \quad (6)$$

where C_k - specific heat of kimberlite; $P_{kimb}=\eta_p \cdot P_g$; $\dot{m}_{kimb}$ - mass of kimberlite destroyed in unit of time; η_p - transfer coefficient of microwave energy to kimberlites; P_g - power microwave generator. Expression (6) does not consider a heat transfer from heated kimberlite in free space. Since heating rate is significant these thermal losses can be neglected. The most important question to determine the energy efficiency of the fracture process is the temperature of kimberlite fracture.

For power estimations of microwave heating to temperature of kimberlite destruction and of heating rate of the kimberlite samples it is required to know the specific heat of kimberlite. Conducted search of the specific heat of kimberlites in the specialized literature has not yielded any results. We executed measuring of specific heat of kimberlites by standard laboratory calorimetric methods. Measuring had estimate character with an accuracy of about 15%. For the evaluation of destruction processes the average value of specific heat is C_k=1.1 kJ/(kg·K). Averaging was carried out by type of kimberlite and its moisture content. The measured specific heat of kimberlites in different samples differs no more than on 30%. The measurements of the specific heat for "wet" kimberlite differ much by not more than 5%. Accepted value C_k=1.1 kJ/(kg·K) is not strongly different from specific heat of similar materials (basalt - 0.85 kJ/(kg·K); granite - 0.65 kJ/(kg·K); volcanic lava - 0.84 kJ/(kg·K) at 20 °C).

Magnetron generator with a frequency of 2.45 GHz and microwave power 600 W was used to research fracture of kimberlites. The high-voltage power supply of magnetron allowed to adjust anode current and was powered by a single-phase AC 220 V, 50 Hz. Control of the microwave power was carried by the anode current of magnetron. The tunable cylindrical resonator with TE111 mode was used as working chamber for destruction of kimberlite. This cavity has a large value of the electric field E_r, transfer efficiency of microwave power to the heated rock, acceptable size and convenient system of resonant frequency adjustment. Cavity had a magnetic coupling element and the flange.

Kimberlite was introduced into the cavity through the sliding cover and placed in the maximum electric intensity E_r in the centre on the wall cavity. In a resonator upper there was the hole with below-cutoff waveguide for temperature performances measuring of kimberlites fracture processes. On lateral cylindrical wall of the resonator there was the below-cutoff grid for visual fixation of destruction.

The experimental installation consists of the following elements: power supply, a magnetron, a rectangular waveguide adapter 90×45 mm, the phase shifter and tunable cylindrical cavity connected. This installation allows to heat up the rocks sample (2-4.5 cm^3) to high temperatures for a few seconds and to investigate impact prompt heating processes of kimberlites destruction.

Measuring of the temperature and a fracture time was executed, fractional composition of the destroyed material was spotted and searching of an optimum regime of fracture was executed on the installation featured above. The general scheme of the experiments is presented at Fig. 7. Pyrometric methods were applied at temperature measuring of kimberlites fracture. The pyrometer placed so that its optical system has been interfaced to the resonator hole and the measuring square of spot has made ~ 5 mm^2 on the heated sample.

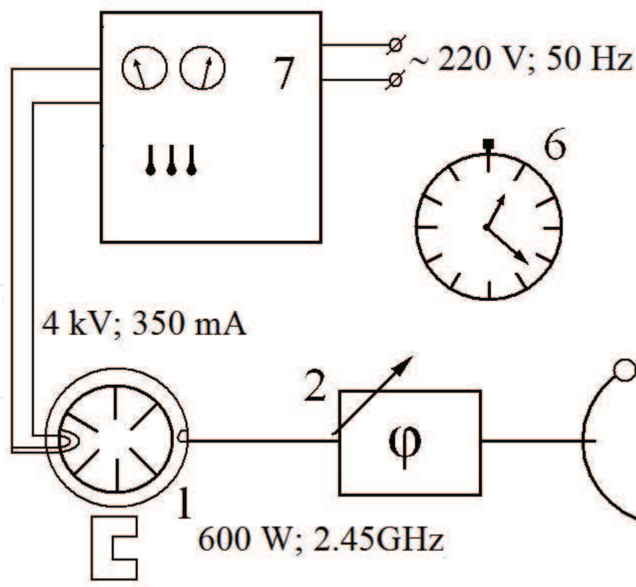

Fig. 7. The experimental setup to determine temperature characteristics of kimberlite destruction: 1 – magnetron; 2 – phase changer; 3 – cavity with kimberlite; 4 – pyrometer; 5 – display block of pyrometer; 6 – stopwatch; 7 – power supply.

It was produced more than 50 samples with a typical size 2.4 cm^3 of the samples kimberlite three types. Their mass was measured. In all experiments sample was heated up during the 2-5 seconds to partial or total destruction accompanied by a strong bang. Partial destruction occurs because of a scatter sample fragments at the beginning of the destruction from zone with intense heating. Temperature and time of the destruction was fixed at the beginning of the destruction process. The microwave generator was switched off on termination of the noise effects. Processed kimberlite extracted from the working chamber. Thus "dry" kimberlite were crushed to pieces of larger size.

The experiments have displayed that efficient processes for the kimberlites destruction begin at microwave heating to 150 °C and at rate of temperature rise of at least 40 deg/sec. Pressure of saturated steams, according Fig. 4, in rocks pores attained $5{\times}10^5$ Pa. Such fracturing temperature at times is less than the temperature of diamond thermal destruction. Experiments on fractional analysis of kimberlite after fracture were executed to describe the technological parameters of the kimberlites fracture process. Kimberlite samples were weighed before fracture with accuracy 5 mg. Fracture is executed under the standard scheme with the control for temperature and time responses. The destroyed samples were removed from the working chamber and carefully separated on three fractions. Each fraction was carefully weighed. Fractions were parted on the characteristic particle size: first (I) - equally or less than 1 mm; second (II) - more than 1 mm and less 2.5 mm; the third (III) - equally or more than 2.5 mm. As a result of examinations the relative fractional composition on weight was the following: fraction I - from 15 to 20 %; fraction II - from 40 to 60 %; fraction III - to 40 %. The fractional composition depend from following factors: the growth rate of the temperature, humidity and structural characteristics of kimberlite, as well as the characteristics and design features of the installation for kimberlites destruction.

Let's execute an energy and technological estimate of kimberlites fracture processes. Assuming the initial temperature equal to T_0 = 20 °C and the final T_d = 150 °C, specific heat of kimberlite C_k=1.1 kJ/(kg·K) and microwave power of 600 W consumed by kimberlites we will gain productivity 4 g/s (240 g/min or 14.4 kg/hour). This theoretical result is close to the experimental value of productivity 2.5 g/sec, which is obtained by research installation. For definition of the complete productivity it is necessary to consider a transfer efficiency of the microwave power to rock in the cavity, which is at 85%, the frequency instability of the generator and a definition of temperature and heat destruction of kimberlites. All these factors will directly affect the performance.

Productivity of installation is of the order 1 t/hour if to use a generator of microwave power of 50 kW and transfer efficiency of microwave energy to kimberlite 80%. For an intrusion of new fracture method in commercial scale it is required installations with productivity ~ 20 t/hour. Productivity growth is limited by the power of existing microwave generators. Besides, the thermal method of fracture was more power intensity than fracture in the wet self-grinding mills. At microwave method the energy consumption per ton of kimberlite fracture increases several times.

However, this method may be more promising and enhance the safety of extracted diamonds. This assumption is based on the fact that linear expansion coefficient of diamond is about an order less than the linear expansion coefficient of kimberlite. The face of diamond will not be pressured the heating and fracturing kimberlite. Diamond is highly nonuniform impregnation. At such method fracture it can appear that the cracking of rock will occur on diamond facets. It is possible that there will be no need for further destruction of the remaining rocks to the size of 1-2 mm. In this case efficiency of installation is considerably risen. Such method of destruction may be able to get the diamonds without any changes that will significantly increase their cost.

Small productivity of designed installation does not allow to investigate the applicability of this method in industrial scale. Investigation of fracture should be performed on a more productive installation, where the kimberlite heating will be carried out during its spilling through the cavity (Prokopenko & Zverev, 2008).

Experimental installation of resonator type with microwave power P=5 kW and a frequency f=2.45 GHz is developed in NRNU MEPhI. Its productivity is not less than 80 kg/hour. The working camera of installation is used cylindrical cavity with TM020 mode. The resonance wavelength of the cavity does not depend on the resonator length and is given $\lambda=2\pi R/5.521$, where R - radius of the resonator; λ=122.3 mm at a frequency f = 2.45 GHz. On the resonator axis in the first maximum of an electric field the ceramic pipe by caliber of 28 mm is disposed. The resonator had a length of 270 mm and its radius was chosen taking into account its frequency displacement by pipe and kimberlite. Electrodynamics characteristics of cavity are counted and optimized. Designed cavity has transfer efficiency of microwave energy to kimberlite from 75 to 80 % at volume filling of cavity by kimberlite from 0.04 to 0.08 %. The resonator axis is canted on an angle 45°±5° to horizon for sliding kimberlite on the dielectric pipe by gravity. For greater uniformity of kimberlite spilling pipe can rotate around its own axis with changeable velocity and to be scavenged by a stream of warm air. The below-cutoff waveguides on the outputs of ceramic pipe ensure the environmental safety of microwave radiation.

Developed installation based on the magnetron microwave generator 5 kW consists of the following elements: power supply of magnetron, magnetron, plate shifters, ferrite circulator, mismatched segment and the working chamber. Installation is executed under the plan of a frequency control of a magnetron by resonator working chamber. Productivity of this installation would be around 90 kg/hour.

Experimental studies of this installation were performed. Fife or six rubbles of kimberlite with a total volume 16 cm^3 was loaded into dielectric pipe. The coefficient of volume filling of cavity by kimberlite was 0.2%. The effective process of crushing kimberlite rubbles accompanied by a loud bang was started on the microwave power 4.4 kW. The portion of rubble was fractured no more than 4 seconds. With initiation of fracture the new portion of kimberlite rubbles was loaded. The grain size of crushed kimberlite were from (0.1 - 0.5) mm to 5.0 mm. The relative weight of small fractions was not less than 45 % from the total mass of the crushed material. Unfortunately, experiments were conducted on kimberlite without diamonds. There was no possibility to estimate effect preservation of diamonds facets at microwave heating.
Designed installation on spilling fracture of kimberlite was served as a prototype for making of the resonator installation working in geological laboratory JSC ALROSA. Now in geological laboratory the microwave heating processes for fracture of kimberlites are explored in more details.

7. Conclusion

Recent trend of power microwave engineering is presented. Microwave heating for emolliating and fracture of rocks allows to reduce energy consumption in the mining industry, help to convert collected waste and dumps of mining and processing enterprise and protect environment. The survey works by microwave heating of rocks confirmed the prospects of using this method. Installations for rocks destruction already find the application of and processing industry.
Presented in the paper model of the microcracks growth and rocks fracture by prompt and uniform microwave heating explains the influence mechanism and allows to predict the nature of emolliating and fracture of rocks depending on the degree of microwave impact. The effectiveness and mechanism of the emolliating are determined by the dielectric properties and structure of rocks. Therefore, examination of the dielectric characteristics over the microwave range is very important. The dielectric characteristics of many minerals have not been studied at all. Important temperature dependences of the dielectric characteristics were not explored. Modern methods and equipment allow to execute these examinations.
Possibility of making of effective installations of irradiating, waveguide and resonator types for emolliating and failure of rock is displayed. Problems of filling and retrieval of processed rock and safety on an electromagnetic radiation are solved in these installations. Development of working chambers of installations is facilitated at using software packages for modelling microwave devices. Transmission efficiency of microwave energy to rocks in the working chamber can reach 90%.
Studies on emolliating and fracture of rocks by the microwave field are actively carried out in Russia, the USA, Canada, UK and Slovenia. Microwave power action for an emolliating of frozen soils, a loss of strength of various ores containing black and nonferrous metals, a destruction of hard coals and a fracture of kimberlites are explored. All studies indicated to increase extraction of minerals after microwave processing of rocks. To enhance efficiency of rocks destruction it is offered to process rocks by powerful microwave pulses of micro and nanosecond duration. Using pulse microwave generators will allow to cut the cost of rocks destruction essentially.

The importance of processes examinations of emolliating and fracture of rocks is displayed on example of kimberlites destruction by superprompt microwave heating. The paper presents experimental results to determine the technological parameters of the kimberlite destruction and the effectiveness of new method of fracture. The recommendations about making of spilling type installations are produced. It is shown that the predominant fracture mechanism of kimberlite is the vapor pressure of water in pores of rock. Despite the large power-consuming of microwave heating processes, studies show the applicability and usefulness of this fracture method.
Thus, the accumulated knowledge about the processes of destruction and emolliating of rocks by microwave heating is performed in the present study. It is shown that microwave energy can be effectively used in the mining and processing industry.

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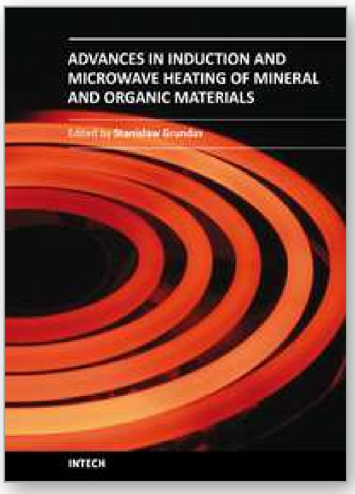

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The book offers comprehensive coverage of the broad range of scientific knowledge in the fields of advances in induction and microwave heating of mineral and organic materials. Beginning with industry application in many areas of practical application to mineral materials and ending with raw materials of agriculture origin the authors, specialists in different scientific area, present their results in the two sections: Section 1-Induction and Microwave Heating of Mineral Materials, and Section 2-Microwave Heating of Organic Materials.

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InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
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Phone: +86-21-62489820
Fax: +86-21-62489821