# ANALYSIS OF SELECTIVE DESTRUCTION CRITERIA OF IRON ORES USING PROVISIONAL MAGNETIC PULSE TREATMENT

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**ABSTRACT**. The paper considers the process of selective pre-destruction of interphase boundaries in iron ores by using magnetic pulse treatment. When analysing the stress-strain state and viscous fracture, the relative similarity of the fracture criteria in the main minerals of iron ores due to magnetostrictive deformation of magnetite grains is shown. It has been established that the strength and toughness of the destruction of magnetite exceeds the analogous properties of calcite in the composition of skarn iron ores, the strength and toughness of quartz fracture exceeds the analogous properties of magnetite. A difference in the character of the destruction of skarn ores and ferruginous quartzites is presented. The criterion for estimating the degree of softening of interphase boundaries in iron ores due to the magnetic-impulse action based on the probabilistic approach is formulated. A theoretical estimate is made of the degree of selective softening of iron ores under magnetic pulse treatment, considering the strength and magnetostriction properties of magnetite. The results of experiments on nanoindentation of interphase boundaries before and after magnetic pulse treatment are presented. By analysing the lengths of developing microcracks under the influence of a nanoindenter, the possibility of reducing the fracture toughness after a magnetic pulse treatment of iron ore is shown.

**Keywords:** mineral processing, iron ores, magnetic pulse treatment

### АНАЛИЗ НА ИЗБИРАТЕЛНИ КРИТЕРИИ ЗА РАЗРУШАВАНЕ НА ЖЕЛЕЗНИ РУДИ ЧРЕЗ ИЗПОЛЗВАНЕ НА УСЛОВНО ТРЕТИРАНЕ С МАГНИТЕН ИМПУЛС

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**РЕЗЮМЕ.** Разгледан е процесът на избирателно предварително разрушаване на междуфазовите граници в желязната руда с помощта на магнитно-импулсна обработка. При анализа на напрегнато-деформираното състояние и вискозното разрушаване се открива относително сходство на критериите за разрушаване в основните минерали на желязната руда, поради магнитострективната деформация на зърната магнетит. Установено е, че якостта и издръжливостта на разрушаване на магнетита надвишават сходните свойства на калцита, като якостта на разрушаване на кварца надвишава сходните свойства на магнетита. Представена е разликата в начина на разрушаване на скарновите руди и железните кварцити. Формулиран е критерий за оценка на степента на омекване на междуфазовите граници в желязната руда, под магнитно-импулсно въздействие. Извършена е теоретична оценка на степента на избирателно омекотяване на желязната руда по време на импулсно-магнитна обработка, като се вземат предвид якостните и магнитни свойства на магнетита. Представени са резултатите от експериментите по наноиндикация на междуфазовите граници преди и след магнитно-импулсно обработване. Чрез анализиране на дължините на образуващите се микропукнатини под въздействието на наноиндентор се демонстрира възможността за намаляване на издръжливостта на пукнатината след магнитно-импулсното обработване на желязната руда.

**Ключови думи:** обработка на минерали, желязна руда, магнитно-импулсна обработка

## Introduction

The whole technological process of ore preparation for enrichment is aimed at the development of conditions that ensure maximum extraction of the useful component and minimise all possible resources (Curry et al., 2014). In order to optimise the extraction of the useful component, it is necessary to perform ore blending properly, then the mixture should be passed through all the necessary crushing and grinding stages to a particle size corresponding to the grain of the useful component and only then it should be extracted by physical or chemical method optimal for this technology (Clout, Manuel, 2015).

When minerals are enriched, the main role of disintegration consists in the complete disclosure of mineral intergrowths with the formation of free grains of components for their subsequent separation according to physicochemical characteristics (Gutsche, Fuerstenau, 2004; Mwanga et al., 2017). Non-mechanical methods of energy impact are very promising in order to overcome the persistence of ores and intermediate products, the disclosure of finely disseminated mineral complexes (Usov, Tsukerman, 2000).

With a comparable size of grinding, ore and non-metallic minerals of hardly-rich ores are revealed to a lesser extent with respect to averagely and easily enriched ores. A lower amount of free ore grains and an increased amount of phenocrysts should be noted for the hard iron ores (Clout, Manuel, 2015).

The influence of mineralogical and petrographic factors on the enrichment is manifested in the nature of the structural features and correlation relationships of the material composition and ore structure parameters with the enrichment indices (Jankovic, 2015).

## Objects and research methods

The object of research is the process of ore preparation using preliminary magnetic pulse treatment (MPT). Research methods are based on the theoretical comparison of the criteria for the destruction of known power models, including the energy criteria for the destruction of the Balandin theory and the theory of viscous fracture by Irwin. Experimental studies are based on the analysis of cracking process by the method of nanoindentation.

## Results and discussion

It is known that the softening effect of magnetic pulse treatment (MPT) can be determined by a number of physical phenomena, such as the magnetostriction of magnetite grains, the inverse non-metallic phase piezoeffect (for ferruginous quartzites), the movement of charged dislocations, etc. (Golovin et al., 1997; Ananiev et al., 2008; Plotnikova, 2013).

MPT is carried out as an intermediate operation of ore preparation before mechanical grinding. Thus, the development of fracture cracks under the action of mechanical loads, at the stage of crushing and grinding, is largely determined by the elastic-plastic properties of the rock. The selectivity of destruction will be determined by the degree of softening of ore and non-metallic phase fusion boundary. Therefore, the magnitude of the contact stresses generated by the MPT at the boundary of ore and non-metallic phases is of great importance.

The criterion of destruction according to the Balandin theory (Karkachadze, 2004) has the following form:

$$\sigma_1^2+\sigma_2^2+\sigma_3^2-\sigma_1\sigma_2-\sigma_2\sigma_3-\sigma_1\sigma_3-(\sigma_{com.}-\sigma_{ten.})(\sigma_1+\sigma_2+\sigma_3)= =\sigma_{ten.}\sigma_{com.} \quad (1)$$

where $\sigma_1$, $\sigma_2$, $\sigma_3$ – main stresses;

$\sigma_{ten.}$, $\sigma_{com}$ – the limits of tensile and compressive strength.

During magnetostrictive volumetric deformation of magnetite grain at the phase separation boundary, compressive contact stresses arise in the radial direction $\sigma_{cont.}$ and tangential tensile stresses, the magnitude of which is two times less than the contact stresses. Then the criterion of destruction will take the following form according to Balandin theory:

$$\sigma_{cont}>\frac{2}{3}\sqrt{\sigma_{ten.}\sigma_{com.}} \quad (2)$$

where $\sigma_{cont}$ is the magnitude of contact stresses at the boundary of the ore and nonmetallic phase caused by magnetostrictive deformation of grain.

If condition (2) is fulfilled, complete destruction will occur at the phase separation boundary. In case of non-fulfilment of the condition (2), partial softening of the boundaries may occur. Table 1 shows the values of critical contact stresses for the main minerals of iron ores.

Table 1. *The value of the critical contact stress for various minerals*

| № | Mineral name | $\sigma_{com}$, MPa | $\sigma_{ten.}$ MPa | The value of critical contact stress |
|---|---|---|---|---|
| 1 | Magnetite | 52 | 14 | 17.99 |
| 2 | Quartz | 120 | 21 | 33.47 |
| 3 | Calcite | 16 | 4 | 5.33 |
| 4 | Hematite | 30 | 6 | 8.94 |

It should be noted that the strength characteristics of rocks and minerals determine the conditions for the destruction of the massif, but do not fully characterise such technological properties as, for example, grindability. This is due to the fact that when an array is subjected to critical loads, a macrocrack develops, the length of which is many times greater than the characteristic size of the mineral grain (Winiarski, Guz, 2008). During crushing and grinding multiple acts of destruction take place. Thus, the disintegration process is characterised by the energy costs for the newly formed surface. So, for example, the Rittinger criterion is used, which characterises the amount of energy costs for destruction directly proportional to the newly formed surface (Bilenko, 1984; Lojkowski, Fecht, 2000): the energy costs for the newly formed surface are characterised by the value of γ (J/m2) - the energy of the newly formed surface unit. The value of γ is related to the fracture toughness (Irwin coefficient) and mechanical properties as follows (Karkachadze, 2004; Winiarski, Guz, 2008; Arutyunyan, Arutyunyan, 2014):

$$\gamma=\frac{\cdot\left(1-\nu^2\right)\cdot K^2}{2\cdot E} \quad (3)$$

where E is the mineral elasticity modulus;

K – the coefficient of fracture toughness by Irwin, $N/m^{3/2}$;

ν – Poisson coefficient.

Table 2. *Calculated values of the specific energy of the newly formed surfaces for various minerals*

| № | Mineral name | ν | E, MPa | K, $10^6$ $N/m^{3/2}$ | γ, $J/m^2$ |
|---|---|---|---|---|---|
| 1 | Magnetite | 0.3 | 215 | 1.25 | 3.3 |
| 2 | Quartz | 0.08 | 96.4 | 1.6 | 13.2 |
| 3 | Calcite (skarn) | 0.3 | 83 | 0.75 | 3.1 |
| 4 | Hematite | 0.14 | 212 | 1.8 | 7.5 |

On the basis of the studies cited in (Goncharov et al., 2006), Table 2 shows the calculated values of the specific energy of the newly formed surface - γ for individual minerals.

Let's compare the fracture criteria for various minerals according to Balandin and Irvine's theories. At that, let's take the properties of magnetite as a standard unit. The comparison results are shown in Table 3.

Table 3. *Comparison of the mechanical properties of minerals with respect to magnetite according Balandin and Irvine's criteria*

| № | Mineral name | Balandin's criterion $\sigma_{cr.}/\sigma_{cr.mag.}$ | Irvine's criterion $\gamma./\gamma_{mag.}$ |
|---|---|---|---|
| 1 | Magnetite | 1 | 1 |
| 2 | Quartz | 1.86 | 3.99 |
| 3 | Calcite | 0.30 | 0.93 |
| 4 | Hematite | 0.50 | 2.27 |

The analysis of the table shows that the difference of the main mineral strength properties according to Balandin and Irvine's criteria have the same character with respect to the properties of magnetite.

As was shown in (Goncharov et al., 2006; Gridin, Goncharov, 2009) the maximum magnitude of the magnetostrictive deformations of magnetite makes λ = 0.6 × 10-4 and is insufficient for the occurrence of critical contact stresses. Therefore, MPT can only provide selective prefracture of ore and non-metallic phase fusion boundary.

Prefracture may begin when plastic deformations occur in the weakest points of mineral fusion zones in a rock (Lojkowski, Fecht, 2000). As a rule, this occurs at the loads of 0.4-0.66 of the critical stress value (Lavrov et al., 2004; Shatemirov, Tilegenov, 2006; Arutyunyan, Arutyunyan, 2014).

Then we assume that the degree of weakening is determined by the following formula:

$$W = \frac{\sigma_{cont.} - k\sigma_{cr.}}{\sigma_{Bal.} - k\sigma_{cr.}} \qquad (4)$$

Let's assume that k is in the range of 0.4–0.66 of σcr, which allows us to estimate the degree of intergranular softening (Goncharov et al., 2006). The calculated values of softening degree of softening lies in the range from 0 to 20%.

Table 4. *Results of ferruginous quartzite nanoindentation with MPTs and without MPTs*

| Sample № | Processing type | Crack length C, mcm | $C_{proc}/C_{cont}$ | Δ=($Kc_{proc}$)/($Kc_{cont}$) |
|---|---|---|---|---|
| 1 | Control (without processing) | 29.48 ± 3.0 | 1.12 | 1.19 |
| | MPT 1 | 33.1 ± 4.2 | | |
| 2 | Control (without processing) | 32.0 ± 4.6 | 1.01 | 1.02 |
| | MPT 2 | 32.4 ± 2.7 | | |
| 3 | Control (without processing) | 36.8 ± 5.5 | 1.07 | 1.11 |
| | MPT 3 | 39.5 ± 6.0 | | |

In (Turin et al., 2013), were shown the results of ferruginous quartzite magnetic pulse treatment influence studies on the fracture toughness coefficient at the magnetite and quartz fusion boundary. The evaluation of fracture toughness coefficient (Kc) at the phase boundary was carried out by nanoindenter introduction into the region of magnetite and quartz fusion (Turin et al., 2016).

The analysis of Table 4 results shows that the reduction of the fracture toughness coefficient with MPT is from 2% to 19%.

## Conclusions

The difference of basic mineral strength properties according to Balandin and Irvine's criteria, with respect to the properties of magnetite, are of the same nature. So, it is permissible to use the Balandin's force model to analyse the nature of selective destruction.

It was established experimentally that there is a decrease in the fracture toughness coefficient within the range from 2% to 19% with MPT, which corresponds to the calculated estimate according to the formula (4), with the following properties of magnetite: magnetostrictive deformation $\lambda = 0.6 \times 10^{-4}$, ultimate compressive strength $\sigma_{com}$, = 52 MPa, tensile strength $\sigma_{ten.}$ = 14 MPa.

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