Introduction

Nowadays the acoustic emission (AE) method becomes more and more important in different field applications, such as mine stability control (Rasskazov et al., 2017), or control of boreholes for oil and gas extraction. On the other hand it is a powerful method to model fracture process in lab in order to determine failure criteria depending on rock mineralogy and structure. AE method is used to fix remotely the critical phases of irreversible stress-strain behaviour of rocks. The progression of irreversible deformation in hard rocks leads to dynamic events such as rockbursts, and in soft rocks to borehole collapse, for example. The precursor of any rockburst is a longtime factor of microcrack accumulation, nucleation and finally failure incident. Microcracks are generated from the rock flaw structure which in turn is determined by mineralogy of rock material. In this work we have tested two types of rock extracted from the PhosAgro apatite mines, Kola Peninsula, Russia – soft with the content of $P_2O_5 \approx 8 - 14 \%$, and hard with the content of $P_2O_5 < 4 \%$. It is important to find out how does the polycrystalline structure of rocks influence the energy of fault process zone. For mine application it means that we can estimate the energy of possible failure depending on rock type and thus to assess a risk level of a certain technology process under mining conditions. To study the process zone formation under controlled conditions, laboratory experiments are carried out on the 40 MPa of confining pressure.

The goal of this work is to study the brittle and the ductile behaviour of rocks, to calculate the related AE parameters of rock fracturing and to find the relevant interpretation of the different indications of faulting for these reology types. The experimental setup we use consists of the servo-controlled loading frame MTS 815 4600 kN equipped with a triaxial deformation cell and AE transducers (ErgoTech Ltd., UK). To register and to store AE signals we use the ASC Milne Trigger Data Acquisition System with 18 AE channels activated.

Method

To study the AE failure criteria we have tested the cores taken from the ore body (soft), and from the enclosing rocks (hard). The cores have been prepared carefully of 125 mm height and 50 mm diameter. Then each core is put into the rubber core sleeve to isolate a core from the oil and AE transducers to install. When this set is installed into the pressure vessel and confining pressure is of 40 MPa value, we apply an axial loading with the strain rate of 0.01 mm/min.

For each laboratory test we calculate the AE locations with the use of ASC InSite Seismic Processor and the statistical values – AE activity and amplitude distribution called $b$-factor – with the use of self-developed software. To estimate a relative magnitude between AE events a location magnitude parameter $M_L$ is used in InSite Seismic Processor. $M_L$ is automatically calculated for each successfully located event using the AE sensors that were used in the location algorithm:

$$M_L = \log \left( \frac{\sum_{m=1}^{n} (W_{RMS,m} \cdot d_m)}{n} \right)$$

where $n$ is a number of AE sensors, $d_m$ is a distance between sensor $m$ and the source location, $W_{RMS}$ is a standard deviation of each AE signal. Thus in the location magnitude a standard deviation of each AE signal is weighted for a distance to the source.

$b$-factor comes from the well-known Gutenberg-Richter law for earthquakes (Lockner 1993). The $b$ values decrease when the number of high magnitude AE events increases. Thus $b$-factor characterises the elastic energy accumulated in the vicinity of process zone a small portion of which is radiated in acoustic waves. We calculate $b$-factor as follows:


\[ b = \lg \frac{N_{AE}^1}{N_{AE}^2} / \lg \frac{A_2}{A_1} \]  

(2)

where \( N_{AE}^1 \) is the number of AE events greater than amplitude \( A_1 \), and \( N_{AE}^2 \) is the number of AE events greater than amplitude \( A_2 \) \((A_2 > A_1)\). For the AE activity and \( b \)-value calculations only located AE events have been selected. For the \( b \)-value calculation we treat the channel of maximum amplitude value for each AE event. To obtain the trends of AE parameters we apply a successively sliding time window of variable duration along the time axis of each laboratory test.

**Examples**

Results of location analysis are shown in Figure 1. Distributions of AE hypocenters and their location magnitudes characterize a specific fracture pattern for each type of rock. Hard rock performs diagonal fracture pattern which is an evidence of brittle deformation (Figure 1a and 1b). While the soft rock can deform differently – through the formation of pure diagonal fracture (Figure 1c), and the complex fracturing where a vast amount of soft rock is totally crashed at the bottom of the core (Figure 1d). This is a plastic response to the applied stress.

**Figure 1** Photos of fractured rock samples under 40 MPa of confining pressure (left), AE source locations scaled to location magnitude (right): a) hard rock (urtite), 341 MPa strength; b) hard rock (urtite), 523 MPa strength; c) soft rock (ore), 520 MPa strength; d) soft rock (ore), 208 MPa strength.
Then we compare the trends of calculated AE activity and $b$-factor with stress curve for each test. Stress curves and calculated AE parameters for each core discussed earlier are shown in Figure 2 in the same order. Three trends are depicted for each core – stress change (blue line), AE activity change (red line) and $b$-factor (green line) in the course of the test. $b$-factor is shown only for the final stage of fracturing which corresponds to the stress drop. It is seen that in each case the AE activity peaks coincide with the stress drop. These are the AE manifestations of final fracture formation. It is important to mention that for the hard rock core of 341 MPa strength two activity peaks are obtained (Figure 2a). It appears that the first peak indicates the formation of the sub-fracture which can be observed on the AE hypocenter distribution as well (Figure 1a). There we can see a sort of splitting of rupture to the bottom of the core. The AE activity curve patterns for hard rock (Figure 2a and 2b) differ to the AE activity curve patterns of soft rock (Figure 2c and 2d). It is very important observation because it gives us an opportunity to correctly determine AE risk criteria for each type of rock – for soft rock we take 0.33 N/sec, for hard rock – 0.7 N/sec. These values exactly fit to the yield points on the stress curves beyond which the behavior of stress becomes flat and then decreasing. The behavior of $b$-factor trends for hard rock (Figure 2a and 2b) shows that the average value of $b$-factor for less strength core is greater than that for higher strength core. It indicates the radiation of higher value of

**Figure 2** Stress trends (blue line), AE activity trends (red line) and $b$-factor trends (green line): a) hard rock (urtite), 341 MPa strength; b) hard rock (urtite), 523 MPa strength; c) soft rock (ore), 520 MPa strength; d) soft rock (ore), 208 MPa strength.
accumulated elastic strain energy for the higher value of strength. The same we observe for the soft cores (Figure 2c and 2d).

Conclusions

We come to the important results for a practical use in mine industry in terms of risk assessment during excavation process:
1. AE hazard criteria based on AE activity parameter depends on the rock type – for hard rock it is equal to 0.7 N/sec, for soft rock (ore body) it is equal to 0.33 N/sec;
2. AE hazard criteria based on AE $b$-factor depends on the rock type and the strength of material – the higher is strength the less is the value of $b$-factor;
3. Soft rock (ore) performs a plastic response to triaxial compression. The AE signature of ductile property of rock is the higher value of $b$-factor as compared with brittle property. The possible interpretation of this phenomenon could be the following. During the nucleation process and final fracture formation less elastic energy is radiated in ductile material (soft rock) than in brittle material (hard rock). It results in preponderance of small amplitude AE events compared with large amplitude events at the final stage of fracturing. That is why $b$-factor increases for soft rock.

In this work we show an attempt to qualify the brittle behavior and the ductile behavior of different types of rock (ore and enclosing rocks) with the help of statistical AE parameters. The criteria of danger based on these parameters are now successfully implemented in the local control system for rockburst monitoring in the apatite mines on Kola Peninsula.

Further development of AE method and its field applications should move to the solution of dynamic problem which links the energy of each crack to the physical parameters of acoustic emission. Physical AE parameters could be derived from the spectral-correlation processing of AE signals, for example (Rozanov and Tereshkin, 2018).

References

