ACOUSTIC EMISSION AND ULTRASONIC SOUNDING AS A TOOL FOR MIGMATITE FRACTURING

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Abstract

Migmatite from the Skalka region (Czech Republic) was chosen as an experimental rock material. It has a macroscopically visible plane-parallel structure (foliation). The foliation was caused mainly by biotite grain arrangement. Four cylindrical specimens of migmatite with sub-horizontal, sub-vertical and oblique foliation were uniaxially loaded up to failure. A network of 8 broadband sensors was employed for acoustic emission monitoring and ultrasonic sounding. A grid search method with an anisotropic velocity model was used for AE hypocenter localization. The source types of successfully localized events were determined from the average first arrival amplitude. Structural anisotropy of the tested rock material caused the anisotropy of its mechanical properties (peak strength, Young’s modulus) as well as a different fracturing in dependence on the angle between the axial stress and the foliation plane. The combination of tension and shear microcracking together with sliding in biotite basal planes was found to control the failure of specimens with sub-horizontal foliation. Shearing and sliding were dominant in the failure of specimens with oblique foliation. With greater dip of foliation, the role of sliding increased at the expense of shearing. Due to the favorably oriented system of microcracks already present, the shearing and splitting was at the same level during fracturing of specimens with sub-vertical foliation before nucleation began.

Keywords: migmatite, sample filiation, acoustic emission, ultrasonic sounding, uniaxial loading,

1. Introduction

The process of failure of low-porosity rocks depends on their mechanical properties and actual stress and temperature conditions. At low pressure and low temperature, brittle failure is most common. This is a progressive process requiring the initiation, growth and coalescence of cracks (Lockner, 1993). Stress strain behavior of low-porosity crystalline rocks during laboratory compression experiments is divided into four characteristic stages: crack closure, elastic region, stable crack growth and unstable crack growth which leads to brittle failure, (Brace et al., 1966; Bieniawski, 1967; Lajtai, 1974).

The fracturing process of stressed rock begins with crack initiation (σci), which for low-porosity rocks occurs approximately at 40-50% of peak strength (σp) (Cai et al., 2004; Nicksiar and Martin, 2013). After σci, dilatancy begins and stable crack growth follows up to the crack damage threshold (σcd), which is approximately at 80% of σp (Cai et al., 2004). After crossing the crack damage level, there is unstable crack growth accompanied with nucleation of the fault plane (σn) at 97-100% of σp (Rao et al., 2011). The stress drop accompanied with the formation of a macro-scale shear failure plane follows after peak stress is crossed. Throughout stable crack growth, the generation and propagation of tension cracks is supposed to be dominant (Tapponnier and Brace, 1976; Martin and Chandler, 1994). Because the tension cracks are parallel to the maximum compressive stress, they cause a nonlinear increase in lateral strain while the axial strain remains linear with increasing stress. In the plane perpendicular to maximum stress, these tension cracks also decrease elastic wave velocities while increasing elastic wave attenuation, velocity anisotropy and shear wave splitting (Stanchits et al., 2006). After crossing σci, there is an onset in acoustic emission (AE) activity (Eberhardt et al., 1998). When isotropic material is fractured, random space
distribution and dominance of tension source types is characteristic for AE events at this stage of loading (Stanchits et al., 2006).

The crack damage threshold corresponds to the reversal point in the volumetric stiffness curve (Cai et al., 2004). Unstable crack growth follows after $\sigma_{cd}$, already existing tension cracks connect with shear ones, which also initiate new tension cracks and after reaching peak strength eventually lead to failure (Lajtai, 1971). There is an exponential increase in AE activity, AE events cluster around the failure plane and the shear type of sources begins to dominate as the nucleation process starts (Lockner, 1993; Stanchits et al., 2006; Eberhardt et al., 1998). The fracturing process is also influenced by grain size (Lei et al., 1992; Eberhardt et al., 1999), presence of predisposed fault planes (Lei et al., 2004; Petruzalek et al., 2013) and the loading regime (Zang et al., 2013).

The fracturing process of isotropic rocks is well described, but there are only a few studies of the fracturing of anisotropic low-porosity rocks. Shea and Kronenberg (1993) studied the role of mica concentration and spatial arrangement in rock failure under triaxial loading. Rawling et al. (2002) found that the initiation of cracks is mostly affected by the orientation of the weakest mineral relative to the axial stress. Kwasniewski (2007) described the dilatancy process of foliated schist under true triaxial compression. Hakala et al. (2007) thoroughly investigated the anisotropy of mechanical properties and the fracturing process of migmatic mica gneiss.

This paper presents a laboratory study of the fracturing process of foliated migmatite under uniaxial loading and describes a different fracturing behavior depending on the mutual orientation of foliation, microcrack alignment and acting stress.

2. Specimen material and experimental setup

Migmatite, a highly anisotropic rock from the Skalka region in the Bohemian - Moravian Uplands was used as the experimental rock material. Mineralogical analyses showed a plane-parallel arrangement of the clusters of individual minerals in the migmatite specimens. These rock-forming minerals were quartz, potassium feldspar, plagioclase, muscovite, biotite and amphibole.

The average size of the grains was from 0.5 mm (quartz) to 2 mm (mica). The migmatite had a distinct, macroscopically visible foliation. There was also found a lineation in the foliation plane, caused by elongation of biotite - amphibole aggregates. The combination of the foliation plane and lineation in this plane should correspond to the orthorhombic elastic symmetry of the rock matrix.

Detailed P-wave velocity distribution and its changes under hydrostatic pressure loading were measured to determine the elastic anisotropy and primary microcrack orientation (Prikryl et al., 2007). The P-wave velocity was measured on a 50 mm spherical specimen in 132 independent directions (Pros and Podrouzkova, 1975) under hydrostatic pressure up to 200 MPa. At atmospheric pressure, the minimum velocity (4 km/s) direction was perpendicular to the migmatite foliation. The maximum velocity (5.9 km/s) direction lay in the foliation plane in the direction of lineation. The velocity in the foliation plane was within an interval from 5.6 km/s to 5.9 km/s. The orientation of velocity anisotropy did not change during the entire hydrostatic loading experiment up to 200 MPa, where most of the microcracks should be closed. The velocity difference between 200 MPa and atmospheric pressure was caused mainly by the closing of microcracks. The size and nature of the anisotropy of the velocity difference indicated the presence of a microcrack system whose orientation was parallel to the foliation plane. Velocity measurements returned to their original values after unloading. A reversible process of closing the microcrack system parallel to foliation occurred under hydrostatic pressure loading. This experiment confirmed the anticipated orthorhombic symmetry of the rock matrix. The presence of microcracks parallel
with foliation increases the difference between maximum and minimum velocity (magnitude of anisotropy) but does not change the type or orientation of symmetry caused by the rock matrix.

Cylindrical specimens of migmatite 50 mm in diameter and 100 mm in height were uniaxially loaded by means of a digitally controlled MTS815 servo-hydraulic loading frame at a constant loading rate (10 N/s) up to failure. Four specimens with different dip of foliation were tested: sub-horizontal (13°), sub-vertical (81°) and oblique (47° and 67°), as is shown in Figure 2. Two axial MTS extensometers and MTS circumferential extensometer were attached to the specimen to evaluate the relative deformations. Eight broadband acoustic emission sensors (WD - Physical Acoustic Corporation, USA) 1.5 cm in diameter were attached to the surface of the specimens (Figure 1) and were used for acoustic emission (AE) monitoring as well as ultrasonic sounding (US).

![Fig. 1 Experimental setup showing the location of 8 AE sensors on the cylindrical specimen](image)

A high-voltage sine pulse with a frequency of 200 kHz was used as a source of US. This corresponds to wavelengths of 2 - 3 centimeters for velocities from 4 to 6 km/s. The AE and ultrasonic transmission waveforms were recorded by a multi-channel transient recorder (Vallen System AMSY - 5, Germany). This apparatus was set up in triggered regime, the sampling rate was 10 MHz and the length of recorded waveforms was 2,048 points, each point with 16 bit resolution of the A/D converter.

### 3. Processing of measured data

For some specimens, the measured relative axial deformation was not correct due to the contact of axial extensometers with rubber bands which were used to attach the AE sensors. Loading of the dural calibration specimen showed inflection points in the circumferential deformation which should not be present and might lead to misinterpretation of experimental data. From these reasons, the extensometric data were not used in interpretation. The relative axial deformation was evaluated from loading frame displacement using a dural calibration specimen with known elastic properties. Apparent Young modulus was calculated from the linear part of the axial stress-axial strain relation.

A two-step AIC picker (Sedlak et al., 2009) was used to identify the onset times in recorded AE and US waveforms. The precision of this technique, verified by comparison with hand-picked travel times, was ± 0.2 μs. The resultant velocity error should have not exceeded 100 m/s. The measured velocity should correspond to the phase velocity considering the size...
of transducers, length of trajectories between the sensors and frequency range (Dellinger and Vernik, 1994).

The ultrasonic transmission was performed in successive transmission cycles at selected loading levels. Every sensor acted as an ultrasonic wave transmitter while the others acted as receivers in one particular step. A velocity ellipsoid model was calculated as a least square approximation of measured velocities (Petruzalek et al., 2013) for every transmission cycle. A grid search procedure was applied to locate the AE events. Only strong AE events with clear identification of first arrival time were localized. The velocity ellipsoid was used as an anisotropic velocity model. This model showed smaller localization error in comparison with the commonly used isotropic velocity model (Petruzalek et al., 2013). The accuracy of localization of strong AE events was ± 3 mm. That was estimated by the localization of known transmitting sensor position during ultrasonic transmission measurements and by localization of sources generated by the pencil lead breaking.

The first arrival amplitude was automatically determined for each recorded waveform of AE and US. The crack initiation stress \( \sigma_{ci} \) was determined at the point of first decrease in first arrival amplitude of US. The point where the AE cumulative count-axial stress relation changed from linear to exponential was defined as the crack damage stress \( \sigma_{cd} \) (Hakala et al., 2007). Source types of AE events were determined based on the average polarity of first arrival (Zang et al., 1998). Only the source types of AE events located in the middle part of the specimen (z coordinate 25-75 mm, see Figure 1) with little error in the localization process (4 us) were interpreted.

4. Experimental results and discussion

The uniaxial strength and apparent Young modulus (Tab. 1) were determined from the stress strain data. The uniaxial strength (\( \sigma_p \)) showed highest values for specimens with sub-horizontal and sub-vertical foliation, while the specimens with oblique foliation had lower values of \( \sigma_p \). Similar anisotropic behavior of peak strength in dependence on foliation angle was described in (Hakala et al., 2007; Nasseri et al, 1997; Nasseri et al, 2003; Cho et al., 2012). The value of apparent Young modulus increased with the foliation angle, which is in accordance with results published by (Rawling et al., 2002; Hakala et al., 2007; Kim et al., 2012).

Tab. 1 Results of uniaxial experiments. \( \Phi \) – dip of foliation, \( E \) – apparent Young modulus, \( \rho \sigma \) – uniaxial peak strength, \( \sigma \) – crack initiation stress in MPa and in percentage of \( \rho \sigma \), \( \sigma_{cd} \) – crack damage stress in MPa and in percentage of \( \rho \sigma \), \( \sigma_n \) – nucleation stress in MPa and in percentage of \( \rho \sigma \), \( n \) – number of AE events detected.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( \Phi ) [°]</th>
<th>( E ) [GPa]</th>
<th>( \sigma_p ) [MPa]</th>
<th>( \sigma_{ci} ) [MPa]</th>
<th>( \sigma_{cl} ) [MPa]</th>
<th>( \sigma_{cd} ) [MPa]</th>
<th>( \sigma_{cn} ) [%]</th>
<th>( \sigma_n ) [MPa]</th>
<th>( n )</th>
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<td>vv02</td>
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<td>39.1</td>
<td>114.5</td>
<td>51.5</td>
<td>45</td>
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The crack initiation stress (\( \sigma_{ci} \)) was determined at the first decrease of first arrival amplitude of ultrasonic sounding in the horizontal direction which was most perpendicular to the failure plane (see figures on the left side of Fig. 3). Specimens with oblique foliation showed higher \( \sigma_{ci} \) in comparison to specimens with sub-horizontal and sub-vertical foliation. The differences were greater when normalized by \( \sigma_p \), because of lower \( \sigma_p \) for specimens with oblique foliation. Cai et al. (2004) summarized previous results of crack initiation stress determined on various types of mostly isotropic rocks. The crack initiation level was found to be 35-60 %
of $\sigma_p$. Hakala et al. (2007) determined $\sigma_{ci}$ of anisotropic mica gneiss depending on the mutual orientation of the loading axis and foliation. Their results showed only slightly higher $\sigma_{ci}$ for specimens with oblique foliation (49% of $\sigma_p$) compared to ones with sub-horizontal and sub-vertical foliation (41% of $\sigma_p$). The crack initiation in isotropic specimens or in specimens with sub-horizontal and sub-vertical foliation is associated with microcracks parallel to the maximum compression stress. In this case, the ultrasonic method used for determining $\sigma_{ci}$ is suitable and considering its sensitivity, probably more reliable than other methods based on strain or AE measurements. In tested specimens with oblique foliation, crack initiation was associated mainly with shear-type microcracks, for which the ultrasonic method is not so sensitive due to their smaller aperture. The very high values of $\sigma_{ci}$ for specimens with oblique foliation presented in this paper were caused by an unsuitable method for determining $\sigma_{ci}$ in this particular case.

The crack damage level ($\sigma_{cd}$) corresponds to the stress at which the unstable microcracking begins. In this paper, $\sigma_{cd}$ was determined at the beginning of exponential increase in AE cumulative count (Fig. 3). The values of $\sigma_{cd}$ were found to be 90-97% of $\sigma_p$, which is in accordance with the values of $\sigma_{cd}$ (91-97% of $\sigma_p$) published in (Hakala et al., 2007).

Fig. 2 Photographs of fractured specimens and corresponding AE hypocenter distribution

Figure 2 shows specimen scale fractures caused by the failure of loaded specimens. Failure planes were determined based on AE localization. In specimens with foliation angles of 47°, 67° and 81°, the failure planes lay in the foliation plane. One failure plane developed in the specimen with a 67° foliation angle. Several parallel failure planes developed in the specimen with a 47° foliation angle. The development of several extension macrocracks parallel to foliation led to the failure of the specimen with sub-vertical foliation. One shear plane cross-cutting the foliation caused the failure of the specimen with sub-horizontal foliation. Even in this case, the foliation predetermined the orientation of the failure plane, both planar structures had the same strike. The described influence of mutual orientation between the
loading axis and foliation on the failure of stressed specimens is in accordance with the works of Nasseri et al. (1997), Niandou (1997) and Cho et al. (2012). The results of ultrasonic sounding, P-wave velocity and amplitude of first arrival reflected the anisotropic behavior of the fracturing process of all tested specimens (Figure 3), which was most pronounced in the specimen with sub-vertical foliation (Figure 3c, d).

Fig. 3 P-wave velocity (red color), first arrival amplitude (blue color) and AE cumulative activity (black color). Figures on the left side correspond to the horizontal direction most perpendicular to the failure plane. Figures on the right side correspond to the horizontal direction most parallel to the failure plane.

The fracturing process of the specimen with sub-horizontal foliation was dominated by tension-type microcracks up to 94% of peak strength. At 94% of $\sigma_p$, the nucleation phase
began accompanied by a sharp increase in shear-type microcracks. The domination of shear-
type AE events and continued increase of collapse-type AE events were seen as the specimen
approached failure (Figure 4a).

The specimen with sub-vertical foliation was found to have an equal amount (45%) of tension
and shear-type AE events before reaching nucleation phase at 91% of $\sigma_p$, where the
percentage of shear-type AE sources sharply increased. After nucleation began, the amount of
shear and collapse-type AE sources continuously increased as the specimen approached
failure (Figure 4b).

The dominance of non-tension-type AE sources was characteristic for the specimens with
oblique foliation. Nucleation began at 95% of peak strength and was accompanied with
a continuous increase in collapse-type AE sources (Figure 4c, d).

The deformation process of migmatite may be explained as a combination of tension
microcracking, shear microcracking, pore collapse microcracking and sliding. Sliding occurs
on the inclined basal planes of biotite (Shea and Kronenberg, 1993). Because the process of
sliding is slow and shear modulus in biotite basal planes is low, it does not cause AE activity.
The attenuation of elastic waves is very sensitive to tension microcracking. The anisotropic
changes of the attenuation reflect a preferential tension microcracking.

Only in the specimen with sub-horizontal foliation did the microfracturing process resemble
the microfracturing of isotropic specimens with dominant tension-type microcracks parallel to
maximum compressive stress up to the nucleation stress level. The other specimens showed
different behavior with an important role being played by non-tension-type microcracking.
Based on optical microscopy and SEM, Rawling et al. (2002) reported that tension-type
microfractures are dominant in triaxially loaded specimens of biotite gneiss independent of
the mutual orientation between maximum compressive stress and foliation. The different
behavior of specimens tested in this study might be caused by the absence of confining
pressure and by the presence of relatively large amounts of primary microcracks, most of which were parallel to foliation.

In the specimen with sub-horizontal foliation, the tension was active up to nucleation. When the density of extensional microcracks was at the same level as their length, the nucleation process started and shearing dominated. Even if the dip of foliation was small, sliding was also present in biotite and caused the anisotropy of the fracturing process. Based on the results of ultrasonic sounding (Figure 3a, b), the amount of extension microcracks in the direction perpendicular to sliding was higher than in the direction parallel to sliding. The fact that the failure plane had the same strike as the foliation was also induced by sliding in foliation planes.

The combination of shearing and sliding led to the failure of specimens with oblique foliation. Because the process of sliding is slow and shear modulus in biotite basal planes is low, it does not cause AE activity. The decrease in AE activity (Tab. 1) with increasing dip of foliation resulted from the increased role of sliding at the expense of shearing.

Before nucleation stress was reached in the specimen with sub-vertical foliation, the combination of shear and extension microcracks was found to dominate the fracturing process. At this stage of fracturing, the relatively high amount of shear-type events was caused by the interactions between favorably oriented primary microcracks already present.

5. Conclusions

The anisotropy of mechanical properties was determined based on the interpretation of uniaxial loading tests on specimens with different dip of foliation. The specimens with oblique foliation had lowest peak strength. The apparent Young modulus increased with the dip of foliation.

A new approach based on the decrease of first arrival amplitude of ultrasonic sounding was used to determine the crack initiation stress. Even if this method is not suitable for specimens with oblique foliation, it should be very sensitive and probably more reliable than methods based on AE and strain measurement in the case of isotropic specimens.

Based on the results of ultrasonic sounding, the fracturing process was found to be anisotropic for all tested specimens. The mutual orientation between foliation and maximum compression stress determined the failure mode of tested specimens. The combination of tension, shearing and sliding was found to control the fracturing of the specimen with sub-horizontal foliation. Shearing and sliding were dominant in the fracturing of specimens with oblique foliation. With greater dip of foliation, we found an increasing role of sliding at the expense of shearing. Due to the favorably oriented system of microcracks already present, shearing and splitting was at the same level during fracturing of the specimen with sub-vertical foliation before nucleation began.

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