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Development of fracture processes in Silesian Carboniferous sandstones

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The development of fracture processes in selected Carboniferous rocks from the Upper Silesian Coal Basin is described, with particular regard to the behaviour of rock specimens in the post-failure stage. The fracture processes were monitored using the stress-strain relations, coupled with acoustic emission, recorded during loading. Energy accumulation and dissipation phenomena were observed during rock loading. Cracking was recorded on the stress-strain curves as deformation loops, accompanied by significant stress decreases, and as cyclic increases in acoustic emission activity. Observing and analysing stages of high acoustic emission and stress drops enabled determination of three ways ("schemes") in which fracture originated and developed during the post-critical stage. Scheme I is damage and movement of grains and rock cement, scheme II is destruction of single rock grains of particular resistance, and scheme III is a dislocational and slide deformation of the rock medium.

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INTRODUCTION

The brittle fracture process, separation of structural bonds, propagation and the mechanism of crack creation are, in the opinion of many scientists, the most important factors causing weakening and failure of rock material (Tapponier and Brace, 1976; Kranz, 1979).

The development of the processes leading to rock failure is influenced by lithology and structural variability. Therefore, studies of evolution of the fracture process include both observation of rock *in situ* in outcrops and excavations, as well as laboratory experiments on samples. Despite many limitations, laboratory experiments are the most popular and important element of research of rock mass properties. Laboratory monitoring of the fracture process is particularly important and according to Brady (1977), reflects mechanisms of rock failure occurring during large and medium scale events (e.g. earthquakes).

The fracture process in rock material loaded in laboratory conditions takes place in stages. During the first stage of the process, location of future cracks is important. These zones of reduced strength act to concentrate stresses, in which the development of defects is initiated. New fractures, emerging in loaded rock, are initially distributed randomly. They propagate in a stable and controlled way, appropriate for given stress conditions. After a stress level, characteristic for a given rock, is crossed, they undergo condensation and integrate into zones of fracture concentration. This means that an uncontrolled, self-maintaining propagation of fracturing takes place, which causes first a macrocracking in a specific direction, and then — emergence of a failure surface. It should be emphasised, though, that in most cases of rock material under load, regardless of crossing a critical stress value (σ_{max}), loss of strength is of local character, and the cracked medium transfers the load further, going many times through consecutive stages of cracking development from microcracking and immediate loss of strength.

The full fracture process of rock material under increasing load thus includes the pre-failure (pre-critical) stage and the post-failure (post-critical) stages. The pre-failure fracture process, both theoretically and experimentally, is much better known than the post-failure fracture process.

Thus the main subject of this work was to analyse the process of rock fracturing at the post-critical stage of rock deformation. In order to attain this research objective lithologically differentiated rocks associated with coal of the Upper Silesian Coal Basin were chosen. The tests were conducted on crump able rocks-schists and sandstones from anticlinal structures that have been of interest to many researchers, notably the first studies of Chmura (1970) concerning the physical and mechan-

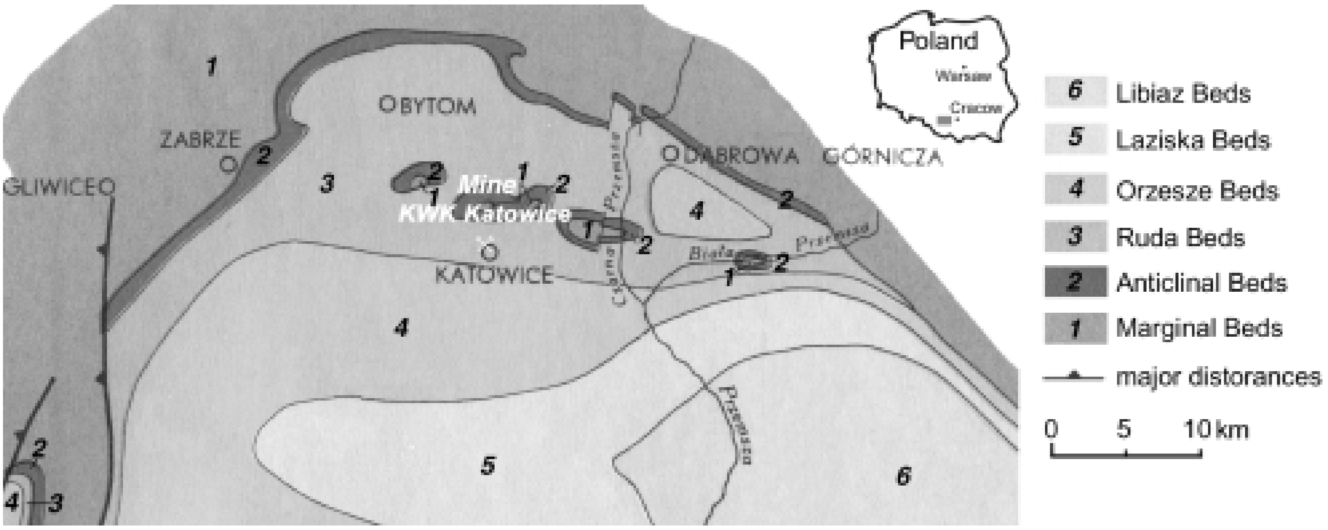

Fig. 1. Location of the "Katowice" Mine on a geological sketch map of the Upper Carboniferous rocks of the Upper Silesian Coal Basin (Sokołowski, 1970)

ical properties of rocks and the latest work of Gustkiewicz (1999) on the physical properties of rocks.

Tests of the post-critical cracking process were carried out in laboratory conditions, and an analysis of the rock samples deformation process was made including acoustic emission events simultaneously recorded on the special test stand in Geomechanics Department, Warsaw University. The fracture process was monitored on the basis stress-strain relations, coupled with acoustic emission, recorded during loading.

CHARACTERISTICS OF TESTED ROCKS

The tests were conducted on spoil-rocks of anticlinally arranged beds associated with the most coal-rich part of the Upper-Silesian Coal Basin. The spoil-rocks comprise schists and sandstones of limnic origin with medium- to coarse-grained sandstones dominant. The samples tested were taken from the "Katowice" Mine at a depth of about 700 m (Fig. 1).

Macroscopic analysis of core sections and samples 58 mm in diameter and height together with petrographic analysis of thin sections allowed to distinction of four rock types:

Type I coarse-grained sandstone**,** grey, of massive internal structure, diagenesis weak, with rare visible coal streaks. The clay matrix composes no more than 15% of the rock. Proportions of quartz exceed 60%, of potash-feldspars about 25%, with several percent of mica and fragments of metamorphic rocks. According the petrographic classification of Pettijohn *et al.* (1972) the rock is an arkose.

Type II fine-grained sandstone, grey, of massive internal structure, often with visible coal streaks. The carbonate-clay cement/matrix composes about 15% of the rock. The rocks contain more than 60% of quartz, about 30% of potash-feldspars, several percent of mica and fragments of metamorphic rocks, mainly quartzites. In the classification of Pettijohn *et al.* (1972) the rock is an arkosic wacke or subarkose.

Type III greywacke has been subject to strong digenesis, compacted, grey, massive internal structure, with significant ferric oxides. The clay matrix composes about 15% of the rock. The rocks contain about 80% of quartz, about 10% of potash-feldspars, and about 10% of rock fragments. According to the classification of Pettijohn *et al.* (1972) the rock is a quartz wacke.

Type IV mudstone grey or dark grey, in places horizontally streaked. Clay content is about 75%. The rest of the rock about

Table 1

Geomechanical parameters of the rocks tested

Type of rock	Volume density [Mg/m^3]	Longitudinal wave velocity [m/s]	Compressive stress [MPa]	Young's modulus [GPa]	Poisson ratio
Coarse-grained sandstone	2.42–2.50	3652–4688	43–97	7.9–14.8	0.17–0.25
Fine-grained sandstone	2.48–2.59	3829–4909	79–115	14.2–19.4	0.16–0.23
Graywacke	2.56–2.71	4424–5567	117–155	15.5–27.0	0.11–0.20
Mudstone	2.56–2.67	3817–4975	42–129	7.3–16.8	0.09–0.16

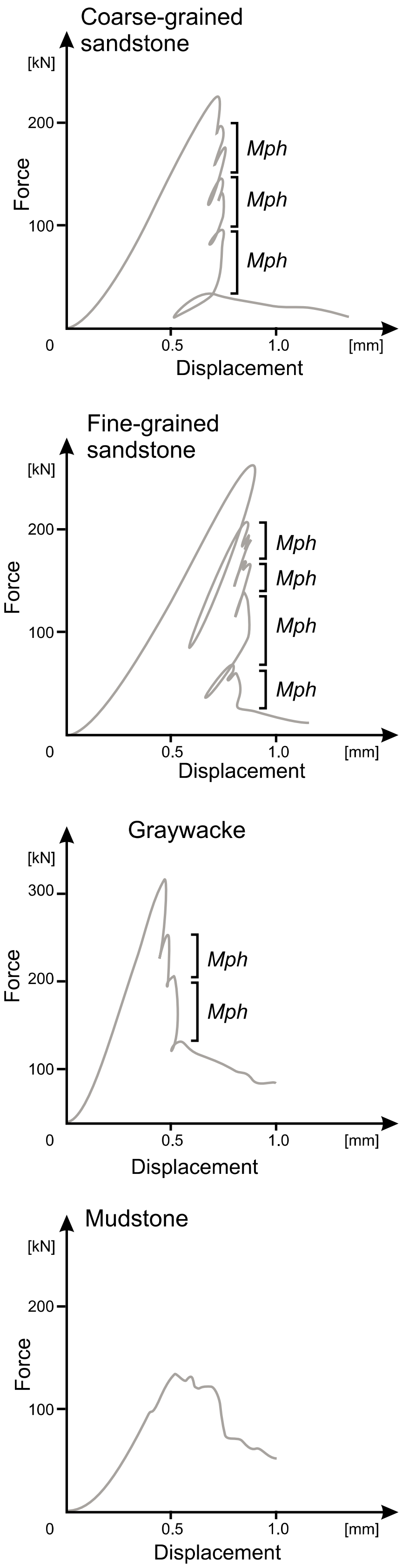

Fig. 2. Deformation curves for the rocks analysed

comprises about 90% of quartz with an insignificant amount of feldspars. According to the classification of Pettijohn *et al.* (1972) the rock is a quartz mudstone.

TEST METHODS

Strength tests were conducted using a special test stand, consisting of a stiff press with electronically controlled load and strain progress (MTS 815) and an analyser of acoustic emission (EA-2) with software for data recording and analysis.

Uniaxial compression tests were conducted so as to fully record the effects of post-failure fracture. When using a stiff press, it is possible to monitor both pre-failure and post-failure stages. The deformation curves obtained in laboratory conditions include the rising branch up to the point where stress reaches its maximum value, and the descending branch. The laboratory control of the post-failure fracture process depends not only upon the rock type, but also upon the test methodology applied. Velocity and mode of loading influence the technical possibility of recording the post-failure deformation branch (Hudson *et al*., 1972; Pinińska and Łukaszewski, 1991).

Laboratory experiments, based upon variants with regard to methodology, conducted using lithologically different rocks from the region of the Świętokrzyskie Mountains (Pinińska, 1994), indicate that in order to ensure the technical possibility of selective recording of post-failure fracture effects, it is necessary to apply loading with an increase of circumferential strain, adapted to the fracture process of a given rock type.

For the Carboniferous rocks analysed, uniaxial compression tests were performed, with simultaneous recording of acoustic emission, and the parameter controlling the load was the declared value of circumferential strain, equal to $0.3 \times 10^{-4}\ s^{-1}$.

During all the compression tests acoustic emission (AE) was also recorded. For this purpose a test set of IPPT PAN was used coupled to the control to the system of the MTS stiff press. The set consists of an accelerometer, a concentric wire, a

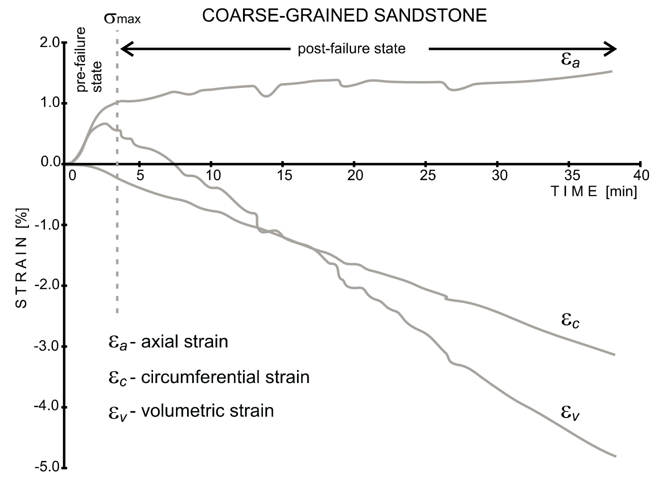

Fig. 3. Axial, circumferential and volumetric strains in the pre-failure and post-failure deformation ranges

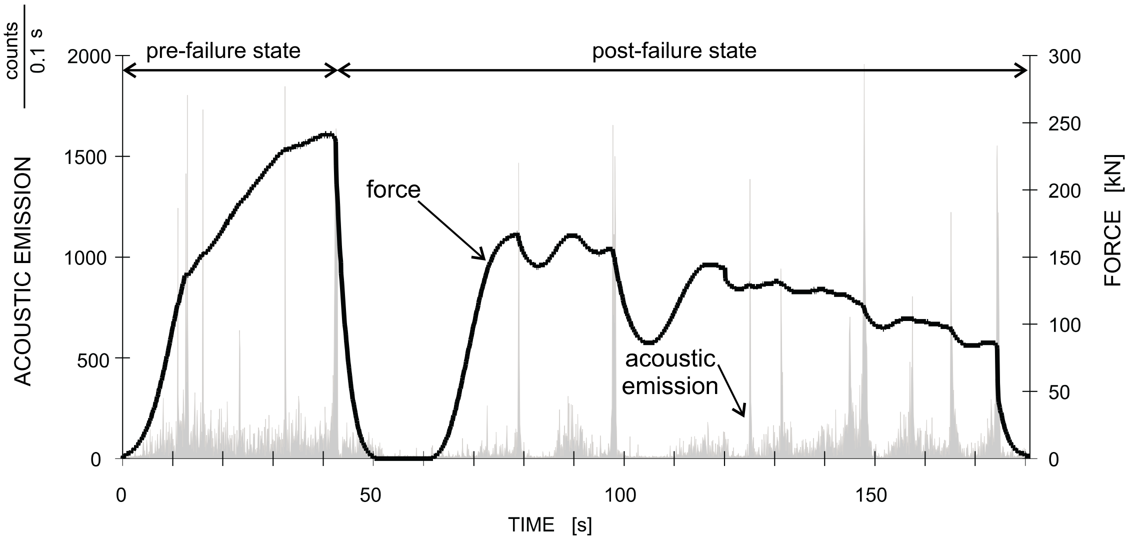

Fig. 4. Acoustic emission during loading of coarse-grain sandstone (H-type post-failure emission model)

preamplifier, an EA-2 analyser of acoustic emission, and a computer with software for recording of acoustic signals in a frequency range up to 30 kHz. The count totals n_z in units of 0.1 s were recorded during all the unconfined compression tests.

Before analysis of the fracture process, the basic mechanical properties of the rocks tested were determined (Table 1).

CHARACTERISTICS OF THE POST-FAILURE DEFORMATION PROCESS

An analysis of deformation curves obtained from the tests indicates that the pre-failure branches do not vary significantly, while differences were observed in the course of the

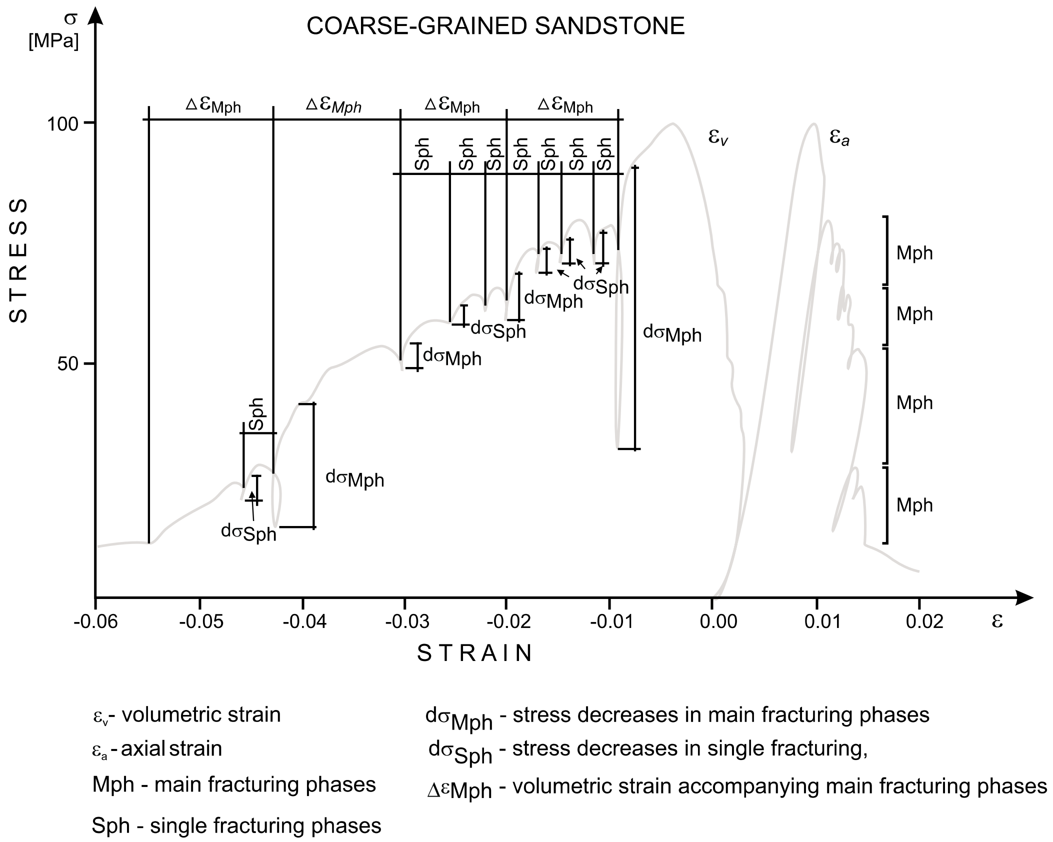

Fig. 5. Stress decreases and strain intervals, corresponding with main and single fracture phases

post-failure branches (Fig. 2). The tests conducted show that the post-failure fracturing stage is much longer than the pre-failure one. This is clearly visible when analysing strains in pre-failure and post-failure stages. During the post-failure stage, between 80 and 90% of full circumferential strain takes place (Fig. 3). From the point of view of the fracture process as a whole, the pre-failure stage is thus relatively short. Fracturing takes place mainly during the post-failure stage, and the rock goes through the states of immediate strength loss many times. This justifies the focus of this work on analysis of rock fracturing in the post-failure stage.

During the course of post-failure fracture, observation of phenomena of accumulation and dissipation of energy is possible. The results of rock material failure are reflected both in curves of stress-strain and in the course of acoustic emission.

In the post-failure branch of the deformation curve, there are visible deformation loops, corresponding with consecutive fracturing stages of various degrees of stress relaxation, depending on the rock properties (Fig. 2). In the course of acoustic emission, on the other hand, cyclical stages of increase of acoustic activity were observed (Fig. 4).

Detailed analysis of the post-failure fracture process was based upon determination of particular fracturing stages. First, the main fracturing phases — macrocrackings on the post-failure branch of deformation curve were distinguished. It was assumed that these phases are limited by deformation loops, characterised by a significant level of stress decrease. Within these phases, consecutive single fracturing phases — microcrackings — were then singled out, characterised by slight stress decreases. The main phases and the single phases appear cyclically on the deformation curve, and they are characteristic of a specific stress condition and a given rock material. Therefore, on the basis of the characteristic stress-circumferential strain, values of stress decreases in main ($d\sigma_{Mph}$) and single ($d\sigma_{Sph}$) fracture phases were then determined, as well as intervals of volumetric strains, accompanying main ($\Delta\varepsilon_{Mph}$) and single ($\Delta\varepsilon_{Sph}$) fracturing phases. A typical example of determination of stress decreases and strain intervals, corresponding to the main and single fracture phases is shown in Figure 5.

The tests conducted showed that strain intervals (Fig. 6) and stress decrease intervals (Fig. 7) accompanying the main and single phases of fracturing vary depending on rock type.

Coarse-grained sandstones are characterised by the emergence of 2–3 main phases, consisting of several single phases. In these rocks, in order for a main phase to emerge, a circumferential strain of between 0.75 and 1.00% is necessary, and for the emergence of a single phase — a strain between 0.08–0.50% must occur. Creation of the main phase and single phase usually results in relaxation of strains up to 15 MPa, up to (in the case of main phases) 35 MPa. Thus in coarse-grained sandstones, the main fracturing phases emerge cyclically, in constant strain intervals, and are accompanied by adequate constant stress decreases.

Fine-grained sandstones are characterised by the emergence of 4–5 main fracturing phases, consisting of as much as a dozen or so single phases. The main phases are usually caused by strains between 0.50 and 1.25% at relaxation of stresses equal to about 15 MPa. At the same time, macrocracking phases can emerge also in wide — up to do 3.00% — strain intervals, causing relaxation of stresses equal to about 85 MPa. Single phases, on the other hand, appear cyclically in relation to strains between 0.07 to 0.50% at decreases in stress of up to 10 MPa. These rocks are thus characterised by multi-stage progress of both main and single fracture phases.

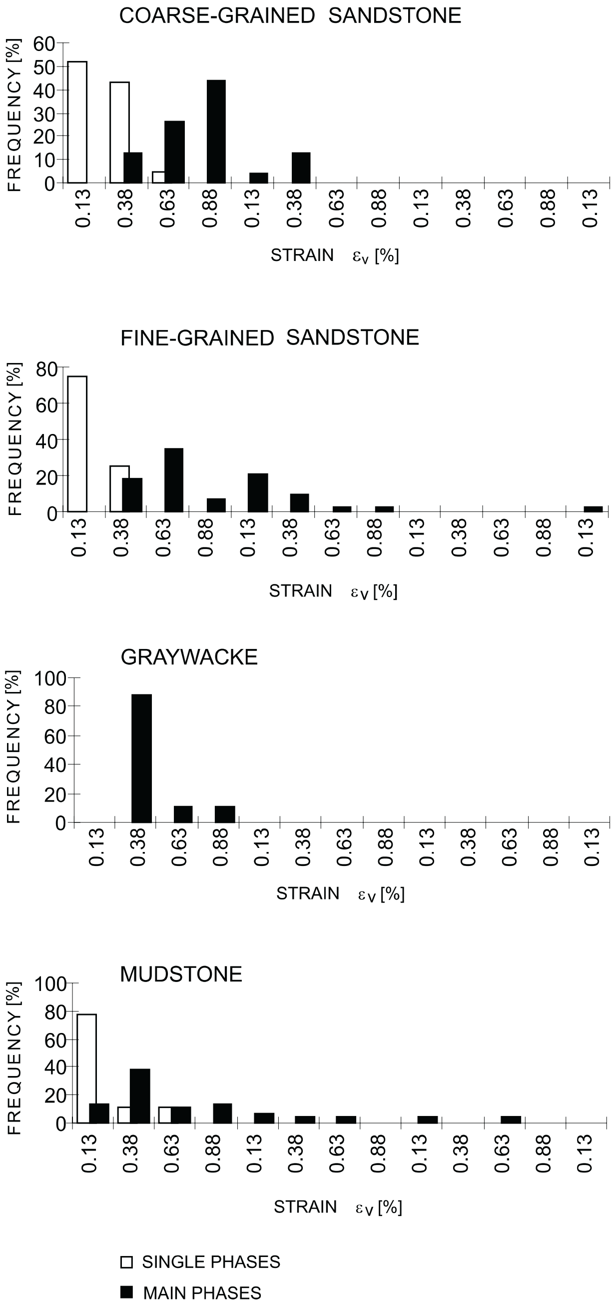

Fig. 6. Volumetric strain intervals, corresponding with main and single fracture phases

In rocks characterised by high strength — greywacke — the fracture energy very often is not dissipated, as a result of which failure of the rock specimen takes place during one or several main phases. Single fracturing phases in these rocks were not observed at all. The main phases emerged in narrow strain intervals at every 0.25–0.50% and were accompanied by stress decreases of varying range: 5–25, 45–50 and even 80–85

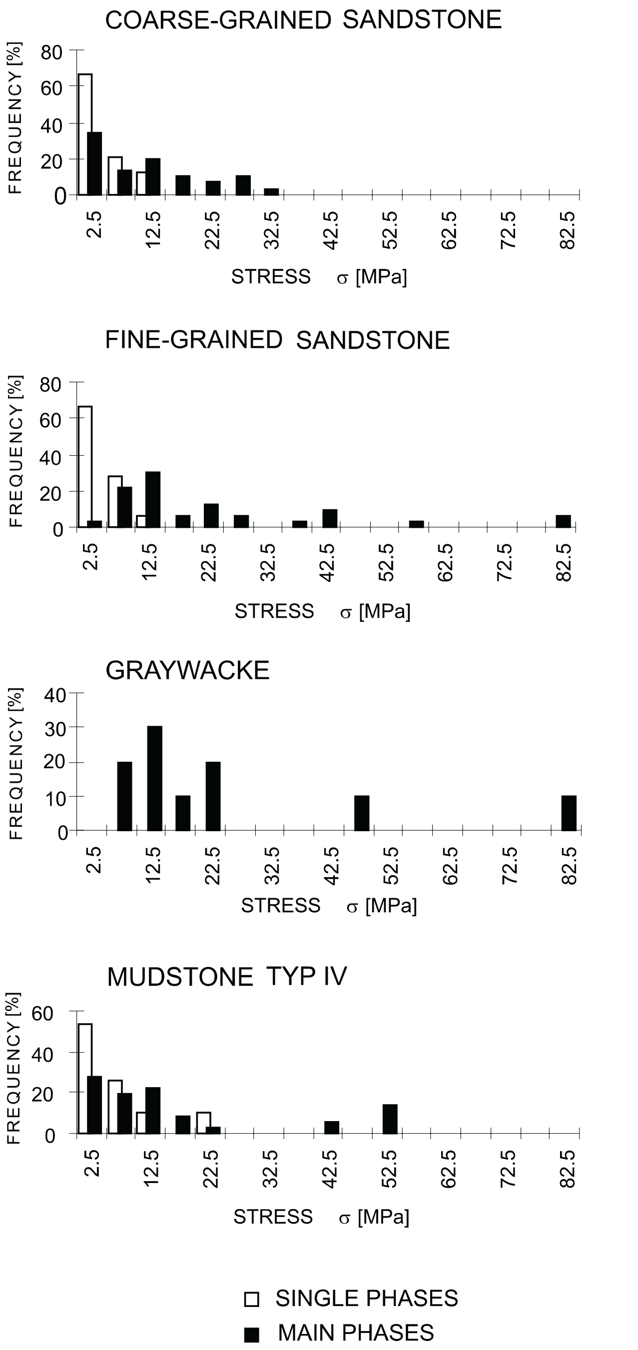

Fig. 7. Stress decreases, corresponding with main and single fracture phases

MPa, and failure often took place in the form of an explosion and within a single, main fracturing phase.

Mudstones, depending upon their lithological and petrographic features, are characterised by two tendencies — either fracturing phases at very variable strain values or monotonic increases in strain. Mudstone rock specimens of greater strength are usually characterised by the emergence of 4 main phases, each consisting of several single phases. Main phases emerge both in narrow (0.25–0.75%) and wide (2.00–2.75%) strain intervals, and single phases most often are repeated at every 0.25% strain value. The main phases and the single phases are accompanied by stress decreases of up to 25 MPa, while these decreases, in the case of the main phases, reach up to 55 MPa.

On the other hand, in mudstone rock specimens of lower strength, in the monotonically declining post-failure branch no main phases are observed, and single phases appear randomly.

As mentioned in the introduction, the fracture effects described are reflected also by acoustic emission. Post-failure acoustic emission can be (Pinińska and Łukaszewski, 1992; Pinińska, 1992) characterised, using three AE models (Fig. 8):

— the H-type model (high) is characterised by a cyclically restarted, high level of acoustic emission, related to the explosive, intragranular fracture of rock material;

— the M-type model (medium) is characterised by post-failure acoustic silence with a final amplification of acoustic emission, related to intra-grain fracture of the rock material;

— the L-type model (low) is characterised by slow fading of acoustic emission, related to monotonic strain increase.

Coarse-grained and fine-grained sandstones, greywackes and mudstones of greater strength can be characterised mainly using the post-failure acoustic emission H-type model of (Fig. 4). and in special cases the M-type (Fig. 9). In these rocks, after the critical strength level (σ_{max}) is crossed, stages of increase and decrease of acoustic activity can be discerned.

On the other hand, mudstones of lesser strength can be characterised, using the post-failure acoustic activity L-type model in which initially we can observe low AE activity, and in the final stage of deformation, emission fades completely (Fig. 10).

The course of post-failure acoustic emission in Carboniferous sedimentary rocks shows convergence with the effects observed on stress-strain curves. Cyclical stages of intense acoustic activity, characteristic of H and M models, correspond with the repeating loops of stress relaxations, and slow fading of emission in the L model is accompanied by the monotonically declining post-failure segment of the deformation curve.

Stages of intensified emission and stress decreases indicate that emergence and development of a single fracture in the post-failure stage can take place in accordance to three schemes (Fig. 11):

Scheme I is characterised by relatively significant, immediate strain decrease. It is accompanied by release of elastic strain energy, which is registered by the acoustic apparatus as a visible increase in emission rate. Further stress and strain increase during energy accumulation is characterised by relative acoustic silence. In the next stage of loading, stress maintains the same, characteristic level during continuous strain increase, and emission can increase exponentially. After a value necessary to initiate macrocracking, an immediate, significant decrease of

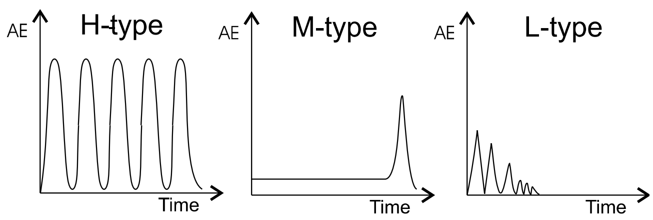

Fig. 8. Models of acoustic emission activity (AE) in the post-failure stage, according to Pinińska (1992)

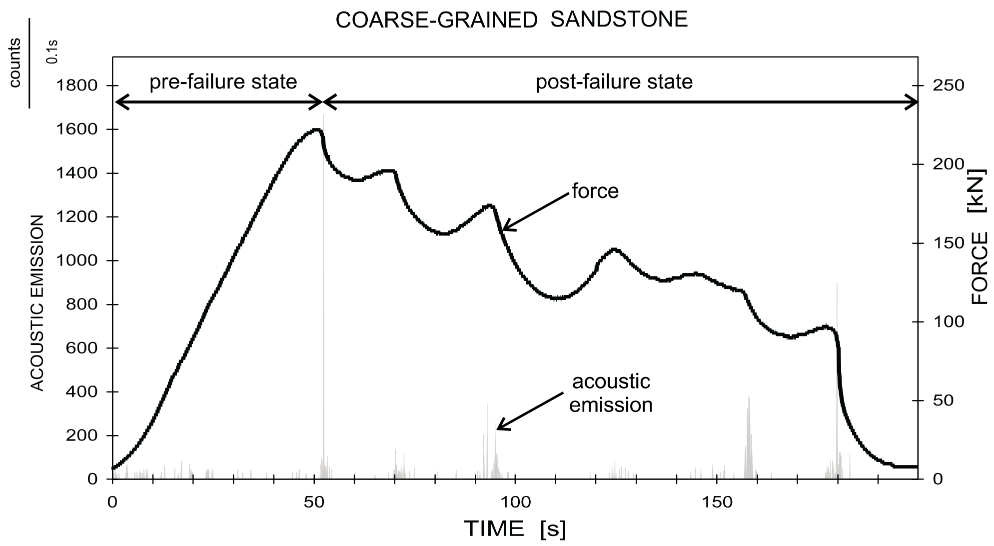

Fig. 9. Model of M-type post-failure acoustic emission

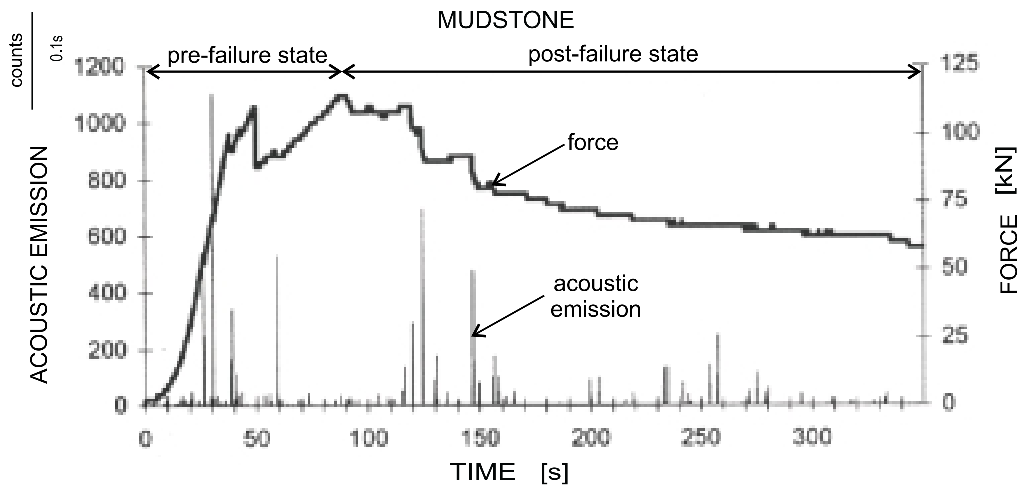

Fig. 10. Model of L-type post-failure acoustic emission

strain takes place, which is accompanied by energy dispersion and another, visible stage of intensified emission. This scheme is related to damage and relocation of grains and bonds and it corresponds with the main fracturing phases of macrocracking.

Scheme II is characterised by relatively small, immediate stress decrease, accompanied by a visible increase of the emission rate. Then it is possible to observe an increase of strain at a constant stress level, and again a small, immediate decrease in stress with a next stage of intensified emission. This scheme is thus related to point wise destruction of single grains of specific strength. Fractures usually run through single quartz grains, and only exceptionally along the grain boundaries, and they correspond with single fracturing phases — microcracking.

Scheme III is characterised by a constant, monotonic decrease in stress along with strain increase, accompanied by very low acoustic emission. This scheme is thus related to dislocational and sliding deformation.

Greywacke, characterised by brittle, violent fracture, undergoes failure in accordance with scheme I. Rock material failure takes place during one, main phase or several main phases of fracturing. These rocks also correspond with the high post-failure model of acoustic activity of H-type.

Coarse-grained and fine-grained sandstones, as well as mudstones of high strength, are characterised by repeated effects of high-energy fracturing, consisting of several smaller effects. In rocks of this type, single fracturing phases shift to main phases after the critical microcracking level is reached.

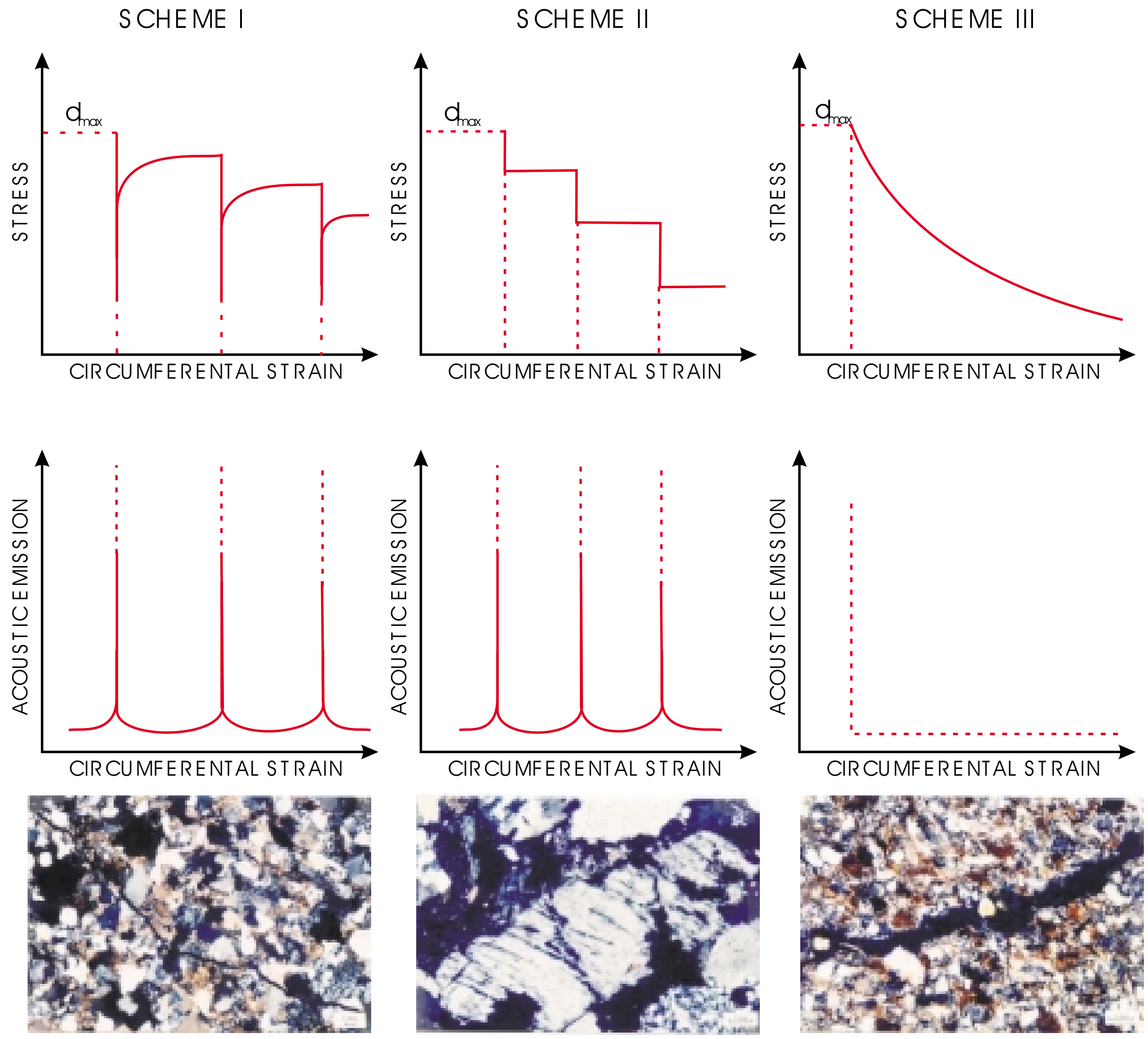

Fig. 11. Schematic diagram of the post-failure fracture process

Fracturing in these rocks thus takes place in accordance with both scheme I and scheme II. On the other hand, the recorded acoustic emission impulses correspond with the post-failure EA model of H-type or M-type.

Mudstones of lesser strength are fractured in accordance with scheme III. They are characterised by slow deformation in form of shifts in the slide zone, thus the fracturing process is stable, despite significant post-failure strains, and a low post-failure EA model of L-type is recorded.

CONCLUSIONS

1. Evaluation of the post-failure fracture process in selected Carboniferous rocks from Upper Silesian Coal Basin was conducted on the basis of:

— analysis of stress-strain relations during of loading of rock specimens,

— analysis of acoustic emission, caused by phenomena taking place in rock material as a result of changes of stress and strain conditions.

As fractures progressed, phenomena of the accumulation and dispersion of energy could be observed in rock media. The effects of fracture of the rock material are reflected in the relations obtained, using both methods mentioned above:

— on stress-strain curves — as deformation loops, usually accompanied by significant stress decreases,

— in the course of acoustic emission — as cyclical stages of acoustic activity increase.

2. Post-failure acoustic emission, recorded simultaneously with measurement of strains and stresses, indicate that:

— Coarse-grained and fine-grained sandstones, as well as mudstones, are characterised by repeated, high-energy fracture effects — macrocrackings, which usually consist of several smaller effects — microcrackings. The character of signals and their distribution in the emission record indicate that fracture takes place both through damage and displacement of grains and bonds, that is, according to scheme I, and through point wise damage of grains, of certain strengths, that is, according to scheme II. The first mode of fracturing is recorded as a post-failure acoustic emission model of H-type, and the second — as model of M-type.

— Greywacke is characterised by violent, brittle fracture during one or several main phases, recorded as repeated signals of high activity (H model), which indicates fracture in accordance with scheme I.

— Mudstones of lesser strength are characterised by slow deformation in form of displacements in the slide zone, and the fracture process is stable, despite significant post-failure strains. Domination of the displacement process over the slide process is indicated by low acoustic activity, which fades as deformation progresses (AE post-failure model of L-type). Fracture in these rocks thus takes place in accordance with scheme III.

3. Comparison of the course of deformation during pre-failure and post-failure stages, and analysis of counts of acoustic impulses shows that, as in many rocks, the stage of pre-failure fracture is much shorter than the stage of post-failure fracture. Fracture phenomena, recorded as deformation loops and acoustic emission effects, are very strongly visible in the post-fracture–post-critical stage, during which the rock specimen undergoes states of strength loss and intensification many times.

REFERENCES

BRADY B. T. (1977) — An investigation of scale invariant properties of failure. Inter. J. Rock Mech. Mining Sc. Geomech. Abstracts, **14**: 121–126.

CHMURA K. (1970) — Właściwości fizyko-termiczne niektórych polskich zagłębi górniczych. Wyd. Śląsk.

HUDSON J. A., CROUCH S. L. and FAIRHUST C. (1972) — Soft, stiff and servo-controlled testing mechines: a review with reference to rock failure. Engine. Geol., **6** (3).

GUSTKIEWICZ J. (1999) — Właściwości fizyczne wybranych skał karbońskich Górnośląskiego Zagłębia Węglowego. Skały warstw siodłowych (in Polish with English summary). Wyd. IGSMiE PAN.

KRANZ R. L. (1979) — Crack growth and development during creep of Barre granite. Inter. J. Rock Mech. Mining Sc. Geomech. Abstracts, **16**: 23–35.

PETTIJOHN F. J., POTTER P. E. and SIEVER R. (1972) — Sand and sandstone. Berlin, Haidelberg, New York.

PINIŃSKA J. (1992) — Emisja akustyczna ośrodków skalnych w stanach naprężeń pokrytycznych. Prz. Geol., **12** (40): 727–733

PINIŃSKA J. (1994) — Właściwości wytrzymałościowe i odkształceniowe skał. Część I. Skały osadowe regionu świętokrzyskiego. Tom I. Warszawa, 30.

PINIŃSKA J. and ŁUKASZEWSKI P. (1991) — The relationships between post-failure state and compression strength of Sudetic fractured rocks. Bull. Inter. Ass. Eng. Geol., **43**.

PINIŃSKA J. and ŁUKASZEWSKI P. (1992) — Rock failure in acoustic emission spectra. Proceedings of XX-th seminar of European Working Group — Acoustic Emission, Leuven.

SOKOŁOWSKI S. (1970) — Geology of Poland – Stratigraphy. Vol.1, Part 1, Publishing House Wyd. Geol. Warszawa.

TAPPONIER P. and BRACE W. F. (1976) — Development of stress-induced microcracks in Westerley granite. Inter. J. Rock Mech. Mining Sc. Geomech. Abstracts, **13**: 103–112.