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Registration of Submicron Particle Emission for Rock Burst Prediction

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Abstract. In recent years the research into the processes of deformation and disintegration of materials at a submicron level has acquired greater importance for different areas of science. Mineral mining at different stages of production is associated with the formation of particles differing in size, including a submicron size range that has a negative environmental effect. However, as it has been proved by laboratory research practice, this effect can be used for rock stress-strained state monitoring both under quasi-static and dynamic types of load. In this work the emphasis is made on the fact that the formation of submicron particles at mechanical loading of rock can be used for its geotechnical monitoring. A new method has been developed for the assessment of the variation of a rock sample stress-strained state implying the registration of the formation of submicron particles from its surface under uniaxial compression. The research results are of scientific and practical interest for solid body disintegration, for rock in particular, and can be used for the development of a new method of virgin rock stress-strained monitoring, registration of dynamic forms of rock pressure occurrence to predict rock burst.

1. Introduction

The growth of mineral mining output, in particular, from deposit mining at great depth, is accompanied by the increase of stresses in virgin rock, sophistication of mining technologies, as well as problems of broken rock transportation, underground workings ventilation, and mining machinery operation. Mineral mining has a negative effect on the formation of natural factors that often result in higher ricks of catastrophic phenomena at mines. Hazardous situations result in downtime of the process equipment and decline of the output, and catastrophic phenomena cause the destruction of mine workings, irrecoverable loss of the expensive process equipment, as well as fatalities that at large has a significant effect on the mining sector economics. Therefore, the forecast of dynamic phenomena, particularly in earthquake endangered regions, acquires particular importance and determines the necessity of perfecting the existing methods of control and development of new hardware, as well as radically new approaches.

Dynamic occurrence of rock pressure has been well studied by Russian and foreign researchers. In spite of a large scope of knowledge about the conditions of the formation of dynamic phenomena and great variety of the existing measures aimed at the minimization of rock burst hazards the issues of rock pressure prediction and monitoring are of ever growing interest today for many researchers in this area.

Rock burst is a physical phenomenon occurring in particular conditions of deformation as a result of the redistribution of rock pressure due to the formation of new vacant space (underground workings) manifesting itself as high-rate brittle fracturing of the strained part of virgin rock (pillar or virgin rock boundary) accompanied by an outburst of rock to underground workings, formation of a shock wave, dust and great sound effect.

The problem of rock burst is an important task of mining, and it is deeply felt in many countries of the world. Numerous works of foreign and Russian researchers deal with the investigation of specific features of rock burst occurrence. Today, numerous different methods and approaches are available for rock burst registration, detection, prediction, and measures for minimization of risk of their occurrence have been developed [1-6].

Iron-ore deposits of Western Siberia occur in seismically active regions and are liable to dynamic forms of rock pressure occurrence, which are characterized by high tectonic stresses several-times exceeding vertical stresses. Variation of physical-mechanical properties of rock was registered in mining at over 1000-m deep ore mines prone to rock burst [7]. It is deemed that in 80-90% of cases rock bursts are provoked by blasting processes, due to which stresses in some parts of workings reach their critical values.

By mechanism and scale the occurrence of dynamic forms of rock pressure is divided into rock burst of local and regional genesis. The first group includes microburst and rock burst causing insignificant damage to mine workings. Regional burst includes shocks, tectonic rock burst and technology-related earthquakes [8]. The main tasks of the problem of rock burst include the development and commercial-scale application of the principles of task-oriented influence on physical-mechanical properties and stress-strained state (SSS) of virgin rock by a system of technological and special engineering measures. By today, a number of preventive measures have been elaborated, and due to them mine workings can be brought into rock- burst risk-free condition by way of the formation of a protective zone due to camouflet blasting, relieve slots and boreholes. In spite of the variety of preventive measures and rock burst forecast methods their occurrence is determined both by natural factors (tectonic stresses, mining depth, specific features of the relief, geological structure of a deposit), and by technology-related factors (mining method, pillar parameters, blasting processes, etc.). Combination of some or other factors to a certain extent may become a compulsory condition of rock burst occurrence. Therefore, it is not possible to completely prevent the risk of rock burst occurrence, because of the fact that these actions present a technology-related component, and the development of new methods of the SSS control with the prediction of dynamic phenomena is rather important.

2. Theoretical background of the formation of submicron particle in the process of rock deformation and breakage

Various technological processes of mining, which provide for superfine fragmentation of rocks are accompanied by the formation of micron and submicron particles [9]. Technology-related dust emission sources also include coal and ore mine shafts, surface mining operations, mineral processing plants, sorting and loading points, rock and ore dumps, tailings ponds, coal and ore storage facilities. Significant amount of dust enters the biosphere in the process of fragmented ROM material transportation to storage sites and processing facilities. High intrinsic energy of rock is the cause of the separation of joints from the exposed surface that can be rather often observed in underground conditions of deposit development as “spalling” and flaking of rock from walls of underground workings, while on a microscale separation and shift of micro- and nanostructured fragments is known as fractoemission [10-12].

Mechanical tests of rock present the most important type of research into their properties, which make possible the investigation of their resistance to deformation and disintegration under the effect of external loads. It is known that deformation and decomposition of rock under the effect of rock pressure and blasting processes are characterized by the initiation and development of the structure defects at different scale levels (micro- and macro fractures), accompanied by the emission of acoustic, electromagnetic, thermal and other impulses. Registration of these impulses is helpful for the identification of the moment of the origin and growth of fractures, as well as their coordinates. These methods are widely dealt with in numerous theoretical and experimental studies of the Russian and foreign researchers [13, 14]. However, application of these methods has a number of constraints, and in some cases their application is not feasible.

It is known that rock breakage is accompanied by the formation of particles differing in size, including submicron size. Particle size distribution depends on physical-mechanical properties of test samples and on the microstructure of rocks. The effect of rock fragment separation from the exposed surface in underground workings is well known, and it characterizes higher concentration of stresses in these areas. Further deformation of an underground working may be accompanied by the accumulation of intrinsic energy in these areas that can result in dynamic occurrence of rock pressure – its disintegration. Thus, rock spalling from walls of underground workings may serve a precursor of rock burst.

3. Peculiarities of cylindrical hole application in experimental studies

It is important to note that a through hole in a sample is an important peculiarity of the research under consideration. It is a macroscale artificial heterogeneity, which size can be varied, and it serves a concentrator of stresses at sample uniaxial compression that allows the recording of the start of the hole surface micro destruction process at the early stage of loading. Besides, this design provides the containment of the hole test volume separating it from particles in the environment.

According to the analytical solution of the task on the effect of the circular hole on the distribution of stresses in a plate exposed to uniaxial compression [15], in this case, some zones with maximal compressing and tensile stresses are formed on the hole contour. These zones are potential sources of particle formation. Micro destruction in the zones with maximal compressing stresses, where stress three-fold exceeds the specified stress, will begin under load P = 1/3P*, where P* is a limit of uniaxial compression load, at which the disintegration of a sample will occur.

Work [16] presents a model of off the scale deformation and disintegration of the cylindrical hole surface at the uniaxial compression of rock where there are two zones: 1 – the zone of disintegrated rock (source of free particles), 2 – the zone of partial disintegration of rock. According to this model, in zones with maximal compressing stresses a rock can be in the off the scale deformation with further disintegration of the hole surface, and, as a consequence, formation of free particles.

On the basis of the authors' physical model of the SSS of a sample with a through cylindrical hole, in conditions of uniaxial compression, the computer simulation has been performed with ANSYS software to identify the zones of stresses concentration in a sample in the process of loading. For the computer model the following material elastic properties, which are typical of ferruginous quartzite, were assigned: Young's modulus of elasticity – 2·10*5 MPa; Poison's ratio – 0.3; volumetric modulus of elasticity – 1.67·10*5 MPa; shear modulus – 7.7·10*4 MPa. The maximum load of uniaxial compression P was 300 kN. The sample computer model was exposed to uniaxial compression during 600 seconds with a load step of 1 second. Figure 1 represents the graphic presentation of the distribution of compression and tensile stresses in a sample with a cylindrical hole in conditions of uniaxial compression, the analysis of which results shows that in the zones of the maximum compression stresses effect the values reach 570 MPa, i.e. nearly three times exceed the values of the sample uniaxial compression strength. In contrast to compression stresses the maximum values of tensile stresses reach only 84 MPa, and they are concentrated in some other zones. Thus, the material in zones affected by the maximum compression stresses is in the state of the off the scale straining in the form of a disintegrated material, and, as a consequence, free particles are formed.

Work [17] deals with experimental studies, in which granite samples of cubical shape with a cylindrical hole were exposed to uniaxial non-uniform compression. The results of tests with granite samples have shown that on the contour of a cylindrical hole in zones of the effect of maximal compressive stresses a system of fractures is formed, and separation of fine long flakes is observed. As a result of granite disintegration in these zones the cross-section of the hole takes a shape of a “dog’s ear”. Zones with maximal compressive stresses are potential sources of free particle formation. Micrograph of the cylindrical hole contour in a granite sample in zones with maximal compressing stresses is shown in Figure 2.

a)

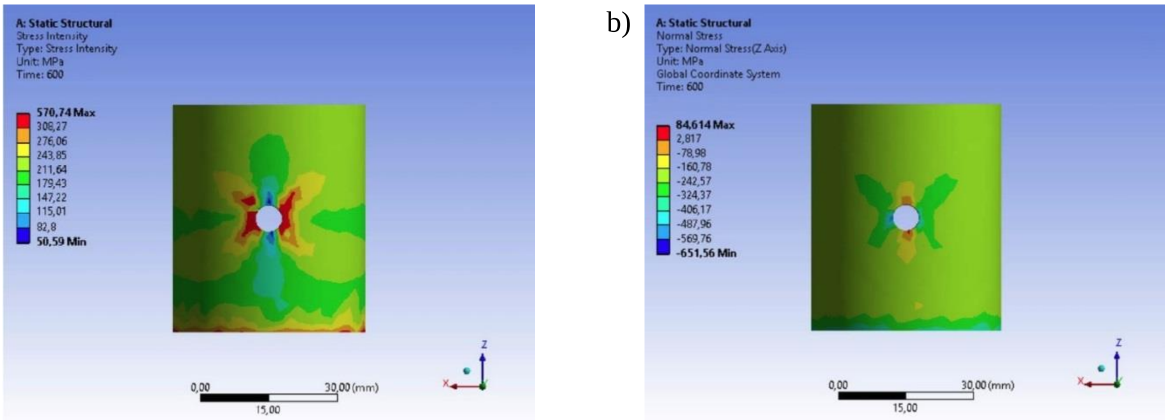


Figure 1. Zones of concentration of compressive (a) and tensile (b) stresses of a sample with a cylindrical hole under uniaxial loading

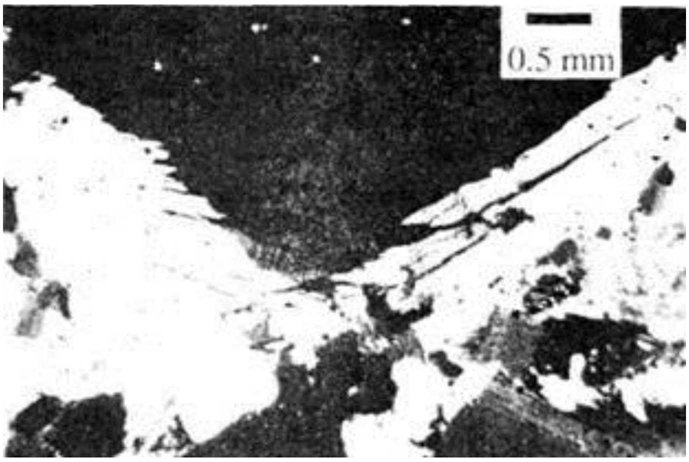


Figure 2. Micrograph of the cylindrical hole contour in a granite sample

From Figure 2 it can be seen that in these areas a clearly visible system of micro fractures is shown. The results of these studies prove disintegration of granite samples in the zone of maximal compressing stresses, and this area is a potential source of free particle formation.

Also, during limestone samples tests the photographs were taken on the cylindrical hole surface after uniaxial compression of the sample before the application of load $P=0.4\sigma^*$, where σ^* is the limit value of compressing stress. Figure 3 shows the photograph, where flaking was registered on the hole surface.

Hole flaking was observed in zones of the maximal compressing stresses. The photograph proves the hypothesis of the disintegration of the cylindrical hole in zones, where, according to the theory of elasticity about distribution of stresses, on the hole contour the maximal compressing stresses are concentrated. In this case, the hole simulates an underground working, while flaking is the result of irregular distribution of stresses (in conditions of real underground working it is the formation of flaw). It is characteristic of the conditions of rock occurrence in virgin strata with high tectonic stresses.

Figure 3. Flaking of the hole surface at the uniaxial compression of a limestone sample

4. Methods and procedures of the research into the emission of submicron particles

For laboratory research the “Program, methods and procedures of experimental studies in laboratory conditions for the assessment of the SSS of rock samples and recording of the rock samples state preceding their decomposition” have been elaborated prescribing the load conditions of rock samples and recording of submicron particles emission.

For the implementation of the planned studies on the basis of the ICEMR RAS laboratory a test bench has been designed and constructed, which is intended for the research into the processes of rocks disintegration at the micron and submicron levels. It makes possible the assessment of the values of critical loads typical of the state preceding the decomposition, which overrunning can become a cause of sample macro destruction. The test bench allows the selection of conditions of sample uniaxial loading with the feature of simultaneous recording of particles emission parameters in six ranges, which are typical of the state preceding the decomposition, for sizes: 0.3-0.5, 0.5-0.7, 0.7-1.0, 1.0-2.0, 2.0-5.0 and over 5.0 μm, with the reference to test time and load applied to a sample. To exclude background concentration of particles in the air of the room, where the research was performed, use was made of a high-performance air filter arresting particles of more than 100 nm size. The test bench is a scientific and engineering stepping stone for the development of a pilot plant of submicron particles emission monitoring in rock mass.

The analysis of the results of the earlier performed research into the formation of submicron particles during deformation and decomposition of various rocks in conditions of quasi-static uniaxial compression of samples with the variation of loading parameters has shown a significant difference both in quantitative and qualitative common factors of particles formation. As 80-90% of rock bumps are provoked by blasting processes, particularly in earthquake-prone regions, wherefore stresses in some areas of mine workings reach their critical values, the results of the performed laboratory research and computer simulation of the dynamic effect on rock samples are of current importance, in particular, for safe underground mining processes in case of the application of combined methods of mineral deposit development.

Samples of cylinder-shaped ferruginous quartzite were selected for tests, as a rule, they were of cubical or cylindrical shape and 4-5 cm length. In the center of each sample a cylindrical through hole of 6 mm diameter was drilled. Figure 4 represents the experimental bench consisted of: test sample with cylindrical hole, hydraulic press, tubes for air sampling, particle counter Hand Held 3016, air filter.

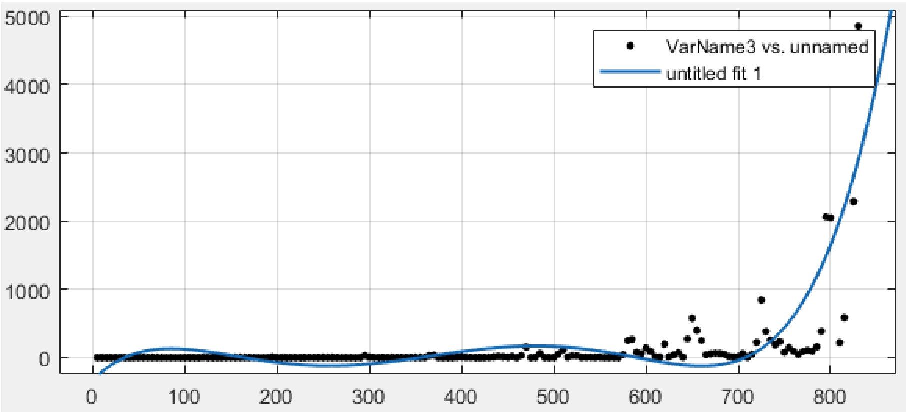
Figure 4. Experimental bench for laboratory investigations of the emission of submicron particles under different loading regimes

The performed suite of studies determines the necessity of the detailed studying of this phenomenon with respect to the development of new recording hardware and method of dynamic phenomena prediction in mineral underground mining.

5. Results and analysis of the test evidence

The performed laboratory studies are aimed at the investigation of conditions of submicron particles formation in different loading conditions. The scope of studies includes samples of cylinder-shaped ferruginous quartzite, which were exposed to uniaxial compression from the zero value to P load of 270 kN in four kinds of loading conditions, in several cycles, which number was chosen depending on the loading rate. The first three kinds of conditions implied staged uniaxial compression of samples, with fixed loading steps of 15 kN, 30 kN and 45 kN accordingly. The loading time of one stage was a constant parameter and amounted to 10 seconds. The loading rates for three kinds of test conditions were 1.5 kN, 3 kN and 4.5 kN per second accordingly. After each loading cycle the sample stayed in a static state during 60 seconds. This approach made possible the monitoring of the dynamics of particles formation not only with the increase of the load applied to the sample, but also in conditions of static uniaxial compression during the whole test time.
For conditions of the performed laboratory studies new qualitative and quantitative common factors of submicron particles emission have been identified for various loading conditions. It has been found that for conditions with the lowest loading rate of 1.5 kN/s the growth of emission amounting to dozens of submicron particles starts at P load of (0.3-0.5)P*, where P* is the load limit value. Load (0.5-0.7)P* is accompanied by the emission of hundreds of particles, and at (0.8-0.95)P* load value thousands and dozens thousands of particles are formed. In conditions with the highest loading rate of 4.5 kN/s the growth of emission is significant, even at a lower load of 0.25P*, hundreds of particles have been recorded, at 0.5 P* load the quantity of particles have reached thousands, while at 0.75P* load – dozens thousands. For conditions with a loading rate of 3 kN/s the quantitative results are intermediate between the above mentioned two kinds of loading conditions. The fourth kind of conditions implied the sample loading at a constant rate of 28.5 kN/min from the zero value to the sample decomposition, particles were recorded at load (0.4-0.8)P*, with a steep increase of their quantity at load (0.9-0.95)P*. Figure 5 shows the results of the research into particle emission at uniaxial compression in different loading conditions.

a)



b)

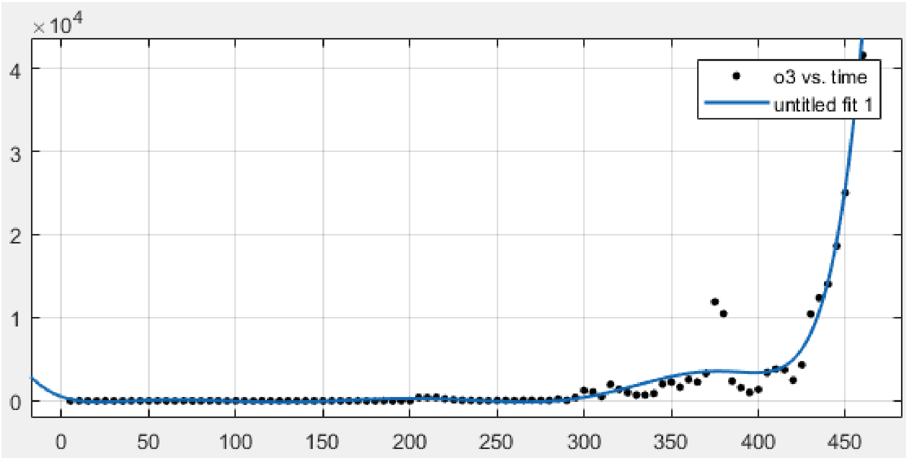


Figure 5. The results of investigations of the emission of submicron particles during the testing of samples of ferruginous quartzites with stepwise loading at a rate of 1.5 kN / s (a) and with a constant loading rate of 0.475 kN / s (b)

It has been found out that:
- the start of submicron particles emission, its intensity and dynamics depend on the rate of uniaxial staged loading of samples that is explained by the energy required for the growth of the existing micro fractures and formation of new ones that results in the rocks disintegration on the surface of a cylindrical hole;
- peak values of particles emission at staged uniaxial loading correspond to the moment of load increase that is the consequence of the growth and redistribution of stresses on the contour of the cylindrical hole;
- the method of rock samples SSS assessment by emission of submicron particles is highly sensitive to external effects that makes possible the recording of the start of the rock disintegration process and monitoring of its dynamics in the process of loading;
- the intensity of particles emission is the criterion of rock sample SSS variation at quasi-static loading, and it is characterized by exponential dependence on the loading value, and it is an indicator of the oncoming macro destruction of a sample;
- the decrease of submicron particles emission under a cyclic dynamic effect on rock samples is explained by the primary opening of the existing micro fractures and the necessity of energy accumulation for the formation of new surfaces.

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The performed studies prove the dependence of submicron particles emission on quasi-static and dynamic loading of rock samples and serve a basis for the development of a new method of prediction of technology-related accidents under the effect of external factors in mineral deposit underground mining on the basis of further selection of criteria of submicron particles emission in case of rock mass uncontrolled decomposition.
The method of the SSS control based on the registration of submicron particle emission radically differs from other known methods, such as acoustic emission, electromagnetic emission, infrared emission, etc., which are informative at the prelimit stage of deformation of a test sample. The advantage of this method is in its capacity to analyze the process of decomposition proper, i.e. rock disintegration, and it helps make judgment on the degree of rock disintegration, i.e., this method can be used for work with a disintegrating material. Estimation of medium stresses in the prelimit area of deformation can be made judging by the state of disintegration on the walls of a cylindrical hole, where stresses three-fold exceed the strength of rock. In respect to field conditions, local application of this method is possible in the areas with high tectonic stresses, in the bearing pressure zone (where virgin rock is in the state of off the scale deformation, and decomposition goes with varying degree of disintegration), etc.
The analysis of the research into the formation of submicron particles and method of their registration has shown that the state of sample destruction is accompanied by a dramatic growth of submicron particle emission that is the evidence of the imminent destruction. Thus, the proposed method will enhance the reliability of forecasts of hazardous dynamic phenomena in mining operations in case of its application together with other known methods.

6. Conclusions

The current knowledge and modern equipment have made possible the development of a radically new method of assessment of the variation of SSS of rock. The results of experimental studies in conditions of the uniaxial compression of rock samples show broad opportunities of further research into this phenomenon in respect to rock burst prediction in mineral mining at burst-prone mines. With this purpose it seems possible to enhance the informative value of data on the state of virgin rock due to the application of the new method, development of the respective hardware and criteria for the assessment of dangerous situations caused by dynamic occurrence of rock pressure.

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