Microscopic observations and interpretations of the progressive fracture in Kuru granite under uniaxial compression

W Wan and C C Li
Norwegian University of Science and Technology (NTNU), Trondheim, Norway
wenkai.wan@ntnu.no

Abstract. Kuru granite is strong and brittle so that it is prone to strain burst. A series of laboratory tests were carried out to investigate the fracturing process in both pre- and post-peak stages under uniaxial compression. The progressive fracturing in the cylindrical specimens was monitored by acoustic emission (AE) technique. The specimens were loaded to different levels both in pre-peak and post-peak stages. After that, the load was removed and two thin sections, one parallel and the other perpendicular to the loading direction, were prepared from each specimen. The fractures in the specimens were microscopically observed. The geometry of each fracture was quantified by its length, opening and orientation. The results show that noticeable fracture propagation occurs mainly at the stress level above 80% of the Uniaxial Compressive Strength (UCS). In general, intergranular cracks dominate in the whole loading process, but after the peak stress the density of intragranular cracks becomes comparable to the intergranular cracks. The percentage of the intergranular first rises and then drops with an increase in the damage of the material. The variation in the number of intragranular cracks is opposite. The intragranular cracks dominate in the beginning of fracture initiation and during the stage of stable fracture propagation, but the intragranular cracks begin to flourish during the stage of unstable fracture propagation. The propagation of intragranular cracks consumes more energy than intergranular cracks. The fracture propagation in the loading direction becomes dominant with an increase in the damage of the rock and finally the specimen fails in splitting. The microscopic observations reveal the fracturing pattern of the burst-prone rock, which are useful data for the study of the physics of strain burst in rock.

1. Introduction
Rock burst is a phenomenon whereby the rock explodes violently in underground rock excavation. It could cause casualties, damage to equipment and delay in excavation operations [1]. Rock burst usually occurs in hard rock. There are two types of rock bursts according to the trigging mechanisms, namely strain burst that is directly associated with stress concentration after rock excavation, and fault-slip burst that is associated with the slippage of pre-existing faults [2]. In strain burst, the rock mass has undergone fracturing and dynamic ejection processes. Therefore, the rock fracturing and the energy transformation process are the two keys in the study of strain burst.

Some efforts have been made on understanding of the fracturing process of rock burst so far. During the early loading period, tensile microcracking dominates the damaging process in the rock; with stress increasing, the shear mechanism will increase [3]. With the help of scanning electron microscopy (SEM) technology, it can be observed that there are obvious differences in the characteristics of the debris
fracture surfaces among rock bursts of different magnitudes [4]. Rock is a multi-mineral aggregate. Cemented boundaries usually are weaker than the dominant mineral grains so that new cracks are nucleated on the grain boundaries, forming intergranular cracks. New cracks may be also nucleated within mineral grains, forming intragranular cracks. During the failure process, the development of cracks in mineral grains and the influence of mineralogy on rock fracture still need further study. This is an important aspect in the physics of rock burst. It is also the focus of this study.

2. Laboratory tests
The granite chosen in the present study comes from Kuru, Finland and it is a brittle rock with mineral grains of various sizes ranging from 0.5mm to 1.5mm. It is composed of 35.3% quartz, 30.4% albite intermediate, 28% microcline and 6% others [5]. Microscopic observations of the thin sections from the intact rock under an optical microscope reveal that the mineral grains in Kuru granite are squeezed into each other in a bumpy contact, forming an interlocking structure. There are a few microcracks and voids inside mineral grains and on the grain boundaries.

The uniaxial compression tests were conducted on a servo-controlled machine GCTS RTR-4000. Each specimen was loaded to a predetermined stress level. Four specimens were loaded to 47% UCS pre-peak, 80% UCS pre-peak, 75% UCS post-peak and 57% UCS post-peak, respectively, where ‘UCS’ represents the uniaxial compressive strength of the rock. For the two specimens loaded to the post-peak stage, their target stress levels can be calculated based on their actually recorded UCS values. While for other two specimens loaded to the pre-peak stage, their target stress levels were estimated according to the average value of the UCS values obtained in the above two post-peak tests. Since the specimens were taken from the same rock cube and the selected granite was quite homogeneous, the estimated values can be considered accurate. After reaching the target stress level, the specimen was unloaded to zero. Figure 1 shows the corresponding stress-strain curves of the specimens. AE technique was used to monitor the progressive fracturing.

![Figure 1](image-url)

**Figure 1.** The stress-strain curves of the four specimens loaded to different levels in the pre-peak and post-peak stages.

Two thin sections, one being parallel and another perpendicular to the load direction, were made from each specimen. Specifically, after the selected areas were cut from the loaded specimens by using a circular saw, an epoxy was used to fill up the flaws and microcracks, as well as to cover the sample surface. The epoxy can glue the debris together and strengthen the samples against the friction from polishing machine. After the epoxy had cured, the samples were glued to the glass slides. Silicon carbide grains with different diameters were used consecutively to grind and polish the surface by a sander. During this operation about 3-5mm depth of sample surface was ground out to get thin enough sections and remove the surface layer affected by the cutting. The final thin sections had a roughness of 0.25μm and a thickness of 30μm. The crack network was extracted on a microscope. The lengths, opening widths and orientations of the cracks were analysed with the help of MATLAB programming.
3. Test results

3.1. Acoustic characteristics during fracturing

Figure 2 presents the variations in two AE parameters—the accumulated AE hits and the energy release rate—that occur during the 57% UCS post-peak test. The acoustic characteristics in other tests were similar. At stress levels approximately below 40% of the peak strength, the original flaws in the rock are gradually closed under compression. The deformation of the rock is dominantly elastic. There are few new cracks initiating. Few AE events appear in this period (figure 2a). After that, the number of AE events starts to increase (figure 2a). These events have small or moderate magnitudes, indicating that the rock enters the stages of fracture initiation and stable fracture growth. With load increasing, the newly created microcracks grow in a stable way. In the meantime, more new cracks are created. A small amount of energy is released accompanying the creation of the new microcracks (figure 2a) and the stress-strain behaviour of the rock becomes more nonlinear (figure 1). When the stress reaches about 80% of the peak strength, the accumulated number of the AE events rises significantly (figure 2). The crack propagation then becomes unstable. The hit rate of the AE events increases remarkably (Figure 2). The rock has been damaged significantly to this stage. Shortly after the stress exceeds the peak, the rock specimen is split by numerous fractures being accompanied by a great amount of AE (figure 2b).

![Figure 2](image)

**Figure 2.** The stress and the AE records (the accumulated AE hits and the AE energy release rates) versus time (a) in the pre-peak stage and (b) in the whole loading process.

3.2. Geometric characteristics of the crack network

In general, the microcracks in rock can be divided into intergranular and intragranular cracks [6]. Microcracks intersect and connect each other to form large fractures, thereby deteriorating the rock. The crack density and the average opening width of cracks are two parameters to quantitatively represent the geometry of the crack network. The crack density, denoted as $D$, is defined as:

$$ D = \frac{1}{A} \sum_{i=1}^{n} l_i $$

where $l_i$ ($i=1, \ldots, n$) is the length of the $i$th crack, $A$ is the area of the crack mapping section. The crack density represents the average crack length per unit area.

The average opening width, denoted as $W$, is defined as:

$$ W = \frac{\sum_{i=1}^{n} A_i}{\sum_{i=1}^{n} l_i} $$

where $A_i$ ($i=1, \cdots, n$) is the opening area of the $i$th crack in the mapping plane.
The intact specimen has a few cracks (figure 3), which are mainly original flaws caused in in-situ state or sampling stage. At the crack closure stage and elastic stage (about below 40% of the peak strength), the changes of crack density and opening width are small in the sections both perpendicular to and parallel with the load direction (figure 3). After that, new cracks initiate (figure 3). New cracks are mainly microcracks with small lengths and widths. The initiation of many cracks indicates that the rock enters the plastic deformation stage. When the stress is bigger than 80% of the peak strength, both crack density and opening width increase dramatically (figure 3). More plastic deformations occur in the unstable fracture propagation stage. The rock gradually loses its bearing capacity. After about 75% UCS post-peak stress level, the rock has been almost destroyed. Crack propagation mainly occurs after the stress is bigger than 80% UCS, which consumes much energy.

Figure 3. (a) Crack densities and (b) average opening widths measured perpendicular to the load direction (S⊥) and parallel with the load direction (S∥) at different stress levels.

Figure 4. Percentages of intergranular and intragranular cracks in the sections perpendicular to the load direction (S⊥) and parallel with the load direction (S∥) at different stress levels.

Figure 4 shows the variations of the intergranular and intragranular cracks in percentage versus the stress level. In general, the intergranular cracks dominate in the whole loading process. The percentages of both intergranular and intragranular cracks vary differently in the pre-peak and post-peak stages. The
percentage of intergranular cracks rises while the percentage of intragranular cracks decreases with an increase in the stress in the pre-peak stage. The variations, however, are opposite in the post-peak stage.

It is believed that the initiated and stably propagating cracks in the pre-peak stage are dominantly intergranular, while the unstably propagating cracks are intragranular. Referring to the AE data shown in figure 2, it can be inferred that the propagation of intragranular cracks is more intensive than the propagation of intergranular cracks. A certain amount of elastic energy will be released accompanying the creation of the numerous intragranular cracks in the post-peak stage. Cracks coalesce to form long fractures and the crack openings increase in this stage (figure 3). To the end, the number of intragranular cracks becomes approximately the same as the number of intergranular cracks. The specimen is finally split into multiple flakes.

After the stress is beyond the level of about 80% UCS in the pre-peak stage, the number of intragranular cracks starts to increase and the crack propagation becomes unstable. Therefore, the rising in the number of intragranular cracks is a sign for unstable crack propagation in the rock.

The directional characteristics of crack propagation often indicate the failure mode of the rock. The fractures in hard and brittle rock often are generated and propagate parallel with the excavation surfaces, which can lead to splitting or slabbing failure [7]. When the released elastic energy is more than the energy necessary for rock fracturing, rock burst will occur.

The dominant orientation of the cracks in hard and brittle rock is an indicator for the tendency of rock burst. It can be estimated by the following method. Assume that it is $n$ cracks in the concerned area (figure 5a). The length of the $i$th crack is projected onto projection line $L_0$ with an angle $\theta$ to the horizontal line. The projection lengths of the crack cluster are summed up and the total projection length in the orientation of $\theta$ is denoted as $\zeta(\theta)$. The projection lengths of the crack cluster in different orientations are obtained by varying angle $\theta$ in the range from 0° to 360°. Figure 5b shows the projection lengths of the crack cluster in the section parallel with the load direction in the specimen loaded to 57% UCS in the post-peak stage. The polar distance to the curve $\zeta(\theta)$ represents total projection crack length. The angle $\theta$ of the longest polar distance on the curve is the dominant orientation of the crack cluster. The orientation factor $\omega$ is defined as [8]:

$$\omega = \frac{\zeta(\theta)_{\text{max}}}{\zeta(\theta)_{\text{max}}}$$  \hspace{1cm} (3)

The value of $\omega$ is between 0 and 1. The smaller the $\omega$, the more predominant the crack propagation is in a specific orientation. The crack orientation factors $\omega$ in the rock sections perpendicular to and parallel with the load direction are presented in figure 6.

![Crack network](image)

**Figure 5.** (a) A sketch illustrating the calculation of the total projection length $\zeta(\theta)$ in the orientation of $\theta$ and (b) the $\zeta(\theta)$ plot for the crack cluster in the rock section parallel with the load direction in the specimen loaded to 57% UCS in the post-peak stage.
The crack orientation factor $\omega$ is between 0.8 and 0.9 from the start of the loading until the stress level of 80% UCS in the pre-peak stage in the sections both parallel with and perpendicular to the load direction (figure 6). That implies that the orientation factor $\omega$ of the original cracks in the rock specimens is approximately 0.8-0.9. After the stress is beyond 80% UCS, the orientation factor in the section parallel with the load direction, S||, starts to decrease and drops to a level of approximately 0.4 when the stress drops to 57% UCS in the post-peak stage, indicating that the crack propagation becomes dominant in the direction of loading. However, the orientation factor in the section perpendicular to the load direction, S⊥, remains in the level of 0.8-0.9 until the end of the test, indicating the cracks propagate identically in all directions in the plane perpendicular to the loading.

Figure 6. Orientation factors of the crack clusters in the sections perpendicular to the load direction (S⊥) and parallel with the load direction (S||) at different stress levels.

4. Conclusions
Four Kuru granite specimens were uniaxially loaded to different stress levels to study the fracturing process in the burst-prone rock. AE technique was used to monitor the progressive fracturing. Microscopic observations were conducted on thin sections cut from the specimens in the directions parallel with and perpendicular to the loading direction. The observations reveal the fracturing pattern in the rock as follows:

- Crack propagation occurs mainly at the stage after the stress is above 80% UCS. At this stage, much energy is consumed to form large fractures with big lengths and opening widths.
- New cracks are mainly intergranular during the stages of fracture initiation and stable propagation, while they are intragranular when fracture propagation becomes unstable.
- Intragranular cracking releases more AE than intergranular cracking does.
- Intragranular cracks are dominantly oriented in the loading direction, finally leading to splitting failure of the specimen.
- Under low confining stress, the fracturing process in Kuru granite is dominated by intergranular cracking, which dissipates a relatively small portion of the strain energy in the rock, with the excess energy being released in a strain burst.

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