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Technical Note

Ghost Kaiser effect at low stress

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1. Introduction

It was experimentally demonstrated that the acoustic emission produced in the material under repeated loading has a specific feature whereby the acoustic emission activity is zero or close to background level when the stress magnitude of the repeated load remains below the previously attained maximum stress (Fig. 1). This is the nature of so-called Kaiser effect, firstly discovered by Kaiser [1] in metals (tested under tension) and then the result in [2] was considered as the Kaiser effect in rock under compression by Kurita and Fujii [3].

Since then a considerable body of research has been directed towards developing the method of recovery of the maximum in situ stress using the Kaiser effect by testing samples made form cores extracted from the locations of interest [3–69].

This method of in situ stress determination is based on undertaking laboratory tests in uniaxial compression. In situ this would be equivalent to having rock samples oriented parallel to the principal directions. Since the principal directions of the in situ stress are not known *a priori*, it was proposed that the cores should be sub-sampled in different directions such that at least three samples will be close to the principal directions [23].

Despite considerable efforts the method still has a number of issues, which makes the in situ stress determination unreliable. One of these issues on which we concentrate here is the appearance of acoustic emission at low stress to strength levels. The source of acoustic emission under compression is believed to be either the generation of new cracks or the extension of pre-existing cracks [2,3,6,7,9,11,13,14,16,18,19,21,22,25,27,29,31,32,35,38–40,43,44,49–51,53,58–60,64–67,69–71]. Hereafter we will refer to this mechanism as *damage accumulation*. It is believed that the onset of this mechanism coincides with the onset of dilatancy [72–76], which corresponds to the compressive stress magnitudes above 20% (20–30% [77], 40% [72–74,76,78–83], or 50–70% [83]) of the UCS. There is, however experimental evidence suggesting that the acoustic emission starts earlier, at much lower stress-to-strength levels. The magnitude of the early acoustic emission right after applying load is comparably low as compared to the magnitude of acoustic emission when the applied stress exceeds the previous maximum stress. Hence it is often considered as a background noise [23].

Other than the early and low magnitude acoustic emission, there have been observations of high magnitudes of acoustic emission activity at low stress. Boyce et al. [84] hypothesised that the initial "burst" of acoustic emission signals in the low stress region was caused by the crack closure in compression. We however note that the successive crack closure creates a concave region in stress–strain curve (Fig. 2). Suppose the sample is loaded to a strain ε_1. This leads to the strain energy stored in the sample (the shaded area under the stress–strain curve) above the energy that would be stored if the material had experienced a pure elastic increase (the double shaded area). This additional energy is supplied by the loading machine (due to increase in the stress in the loading machine). There is however no excess in the energy to be dissipated by the acoustic emission. Furthermore, the crack closure is a continuous process whereby the opposite faces first get into contact and then the contact continuously spreads (Fig. 3). It is this continuity and the absence of abrupt changes that exclude the possibility of formation of acoustic pulses. In addition, to the best of our knowledge, there is no evidence in the literature to support that crack closure can produce acoustic signals under quasi-static loading.

The above consideration forces us to look for the low stress acoustic pulses in the areas of high stress concentration. The first obvious candidate for this is the contacts between the sample ends and the loading platens where the surface roughness (micro-asperities) and/or free particles (e.g., dust or residual material at

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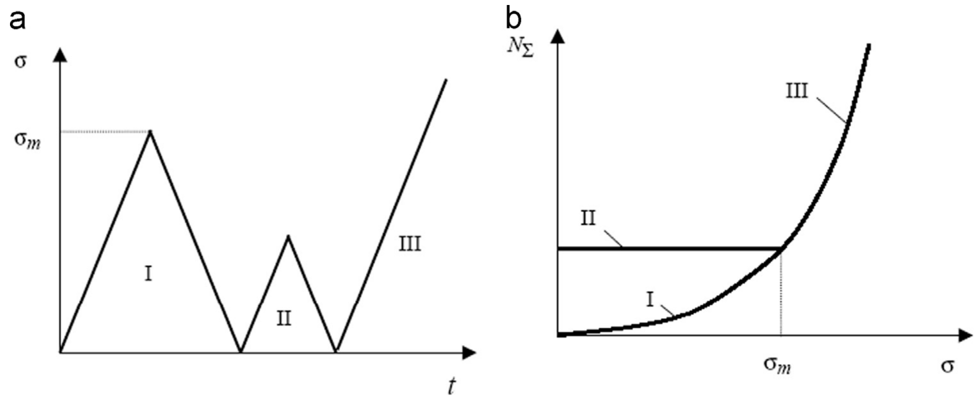

Fig. 1. Kaiser effect in materials and rocks under compression: (a) the loading cycles, and (b) cumulative acoustic emission activities corresponding to these loading cycles [23].

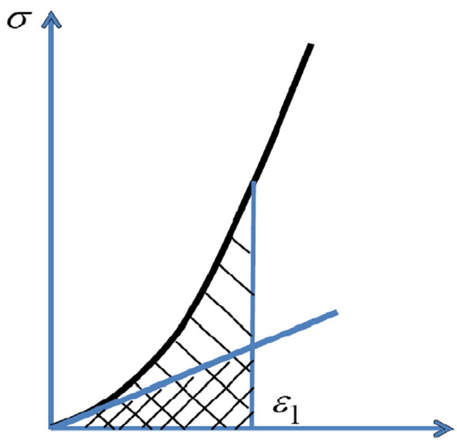

Fig. 2. The concave region of stress–strain curve created by successive crack closure in compression. The strain energy stored in the sample increases at a higher rate than that of pure elastic sample, which excludes the energy excess needed for generating acoustic emission.

the sample ends after grinding) considerably reduce the area of actual contact and thus increase the contact stress.

We performed special experiments to check this hypothesis. We start with artificial samples made of aluminium where the contact surfaces can be very smoothly machined and polished. We then proceed with samples made of agate – these have chemical composition somewhat similar to rocks but are amorphous and very homogeneous and then turn our attention to rock using sandstone as an example.

2. Experimental apparatus and parameters

We tested cylindrical samples of aluminium, agate and sandstone of 18–19 mm in diameter and 40–45 mm in length, as shown in Table 1. Acoustic signals were measured by two piezoelectric transducers from Physical Acoustics Corporation (MISTRAS – Micro 200HF sensor). The transducers were connected through a 40 dB pre-amplifier to the 60 dB front amplifier. The resonant frequency of sensor is 2500 kHz. The acoustic signals were filtered in the frequency range from 1 kHz to 1 MHz. The signal threshold of the system was set to 47 dB. The maximum signal amplitude was 100 dB and the maximum sample rate was 1 M samples/ per second.

The samples were loaded using a servo-controlled loading machine of 5 t capacity. The load was displacement-controlled, applied by the movement of the upper platform, while the bottom platform was fixed (Fig. 4).

The test parameters are listed in Table 1. All samples were prepared in accordance with ISRM standard for unconfined compressive strength (UCS) [85] and acoustic emission testing [86]. In order to ensure the two transducers have same ability/sensibility to pick up acoustic signals at each test, few calibration tests were conducted before starting each test. The calibration procedure was as follows:

1. After placing the sample in the designed condition, a stress (0.1–0.2 MPa) was applied on the sample and kept by the loading frame.
2. Two transducers were attached to the sample under load. In order to ensure that the threshold was sufficient to eliminate the acoustic noise from environment, acoustic emission acquisition system was turned on for around 30 s to confirm there is no acoustic noise recorded by the system when the load is unchanged.
3. An Alan key (10–15 g in weight) was held by hand vertically at the location 1 cm above the top of loading bar plate (Fig. 4). Then, the pencil was dropped vertically so the pencil lead could hit the loading bar plate. The process was repeated three to four times on each test.
4. The transducers were adjusted/rearranged if the number of acoustic emission counts produced by dropping pencil was less than 1.
5. After ensuring the sensitivity of two transducers was similar among all previous tests, the acquisition system was restarted and the load was applied to the sample according to the specification of each test.

3. Tests and results

We tested two aluminium samples (aluminium A and B) which were made from aluminium 6000 series, which is a uniformly crystallised metal. It is often used for calibration of testing equipment. This material has stable physical properties under room temperature and behaves elastically which makes the results reproducible under repeated loading.

Both aluminium A and B were loaded in two loading-unloading cycles. In the 1st cycle (the memory inducing load) the sample was loaded to 20 MPa. In the 2nd loading cycle (the measuring load) the maximum stress was 40 MPa.

In the test result of aluminium A, the acoustic emission starts at a very low stress, less than 5 MPa; that is below 2% of the UCS