Polarization–depolarization process in glass during percussion drilling

A. Rabinovitch†§, V. Frid‡, J. Goldbaum† and D. Bahat‡

† The Deichmann Rock Mechanics Laboratory of the Negev, Physics Department,
Ben Gurion University of the Negev, Beer Sheva, Israel
‡ The Deichmann Rock Mechanics Laboratory of the Negev, Geological and
Environmental Science Department, Ben Gurion University of the Negev,
Beer Sheva, Israel

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ABSTRACT

In addition to short individual high-frequency signals and their strings, which are well known and analysed, electromagnetic radiation measured during percussion drilling of glass showed a group of lengthy pulses usually appearing in pairs (denoted a–b). In order to understand their origin a polarization–depolarization process is invoked. Thus it is assumed that, during drilling, stress is accumulated in the sample, its increase being accompanied by a polarization increase, which is undetected by the equipment. When stress reaches a critical value, large crack propagation (‘chip’ fragmentation) begins, and a group a signal is emitted. Crack propagation causes stress and polarization relaxation, and the latter is detected as a group b signal.

§ 1. Introduction

It is well known that cracks propagating in a material emit electromagnetic radiation (EMR). This phenomenon was discovered by Stepanov (see Urusovskaja (1969)) in 1933 in fractured KCl crystals. In 1973, Misra (1975) detected an alternating magnetic field in the form of decaying pulses induced by fractures in several metals and alloys in tension. In 1975, Nitsan (1977) measured EMR of 1–8 MHz during his experiments on fracturing quartz-containing rocks. In the 1980s and 1990s, many fracture experiments where EMR was detected were carried out on various materials, for example ionic crystals (Khatishvili 1984), rocks (Warwick et al. 1982, Ogawa et al. 1985, Yamada et al. 1989, Rabinovitch et al. 1995, 1998, 1999a,b, 2000, Frid et al. 1999), ice (Fifolt et al. 1993, O’Keefe and Thiel 1995) and glass (Miroshnichenko and Kuksenko 1980). Fracture was induced by tension, by compression (both uniaxial (Warwick et al. 1982, Yamada et al. 1989, Rabinovitch et al. 1995) and triaxial (Rabinovitch et al. 1995, 1999a,b, 2000, Frid et al. 1999)), by bending and by impact (Ogawa et al. 1985). The observed frequencies varied from several kilohertz to several megahertz. EMR pulses were

§ Author for correspondence. Email: avinoam@bgumail.bgu.ac.il.
subsequently parametrized (Rabinovitch et al. 1998), and the following features were found.

(i) The crack length is proportional to the length of the time of pulse growth to its maximum $T'$.

(ii) The crack width is inversely proportional to the pulse frequency $\omega$.

(iii) Thus the crack area is proportional to $T'/\omega$ (Rabinovitch et al. 2000, Frid et al. 2000).

(iv) The EMR intensity depends on the material fractured (Khatiashvili 1984) but does not depend on the fracture mode, tension or shear (Frid et al. 2000).

EMR measurements during impact or percussion drilling are very rare (Ogawa et al. 1985, Goldbaum et al. 2001). Impact experiments include the collision of two feldspars, and the impact of a granite sample by a hammer or by a falling brass sphere, with a simultaneous measurement of the electric field by an electric sensor (Ogawa et al. 1985). The signals obtained had two general parts: sine-like oscillations of several tens of kilohertz, and a change in baseline (see figures 2 and 3 of the paper by Ogawa et al. (1985)). The baseline change is decaying and not periodic. These two parts were sometimes superimposed. Drilling experiments with EMR measurements throughout the entire tests were carried out in our laboratory by Goldbaum et al. (2001) in glass, granite, chalk, Sollenhofen and polymethyl methacrylate (PMMA). In these experiments, five groups of signals were obtained:

- **group 1**: ‘single pulses’ of 0.3–1.5 µs duration with a single main frequency ranging between 10 and 25 MHz (figure 1 (a));
- **group 2**: ‘short strings of pulses’ of 2–15 µs duration consisting of several pulses of the first group type and, thus having a slightly more complicated frequency spectrum;
- **group 3**: ‘lengthy strings of pulses’ of 15–60 µs duration consisting of numerous pulses of the first two groups and with a wide range (11–23 MHz) spectrum;
- **group 4**: ‘lengthy forms’ (e.g. figure 1 (b)), whose duration varies between 10 and 800 µs and which show low frequencies (several kilohertz), baseline voltage changes and also contain lengthy strings of high frequencies of group 3 type;
- **group 5**: a different type of ‘lengthy form’, again decorated by high-frequency strings (figure 1 (c)).

Here we investigate the signals of groups 4 and 5 and analyse their hitherto unknown origin and the significant information that they can shed on the drilling process.

§ 2. Experimental arrangement and materials

2.1. Material

Cylindrically shaped soda–lime glass samples, 10 cm in length and 3 cm in diameter, were percussion drilled. Soda–lime glass consists of a glassy matrix of strongly bound silicon, oxygen and calcium atoms, into which weakly bound sodium ions are introduced. These sodium ions are relatively free to move and provide the main contribution to the electric conductivity of glass (Rzhevskii and Novik 1978).
Figure 1. (a) Typical pulse of group 1 of frequency 14 MHz; (b) typical pulse of group a (appearing in sample 6 at \( t = 0.43 \) s after drilling start; hole depth \( d = 0.23 \) mm) (Goldbaum et al. 2001); (c) typical pulse of group b.

The walls and edges of the samples were carefully polished, so that one could easily see the cracks that appeared as a result of drilling. The bit diameter was 10 mm.

2.2. Experimental arrangement

During the entire tests, EMR was measured in the frequency range 1 kHz–50 MHz with 1 \( \mu \)V sensitivity throughout. The EMR was detected (figure 2) by a one-loop magnetic antenna, 3 cm in diameter placed at a distance of 3 cm from the drilled hole. The antenna is electrically ‘small’ and exhibits negligible response to foreign electric fields. External EMR disturbances were further reduced by the following means.

(a) The sample, together with the antenna, was placed in a grounded Faraday cage. Its construction shielded EMR frequencies up to the order of 1 GHz.

(b) The plane of the antenna was placed perpendicular to the drilling direction, so that it did not detect EMR disturbances emitted by the machine motor.

All EMR signals were electrically amplified by 60 dB, digitized and collected on the hard disk of a personal computer. The data were analysed after the test was completed.
§ 3. RESULTS AND DISCUSSION

3.1. Laboratory results

We have investigated the results of groups 4 and 5 signals (see §1) measured during percussion drilling of glass cylinder samples (Goldbaum et al. 2001). These signals occurred in five glass samples 2, 3, 4, 5 and 6. Here we denote signals similar to that depicted in figure 1(b) as group a signals, while those similar to figure 1(c) are called group b signals. Group a signals are similar to individual EMR pulses (Rabinovitch et al. 1998), but their frequencies are smaller (several kilohertz). Group b signals consist of a sharp voltage 'jump' (of a duration of about 3% of the whole pulse duration), and ranging in size between 6 and 12 μV; the high voltage remains more or less constant for a period that varies between 10 and 1000 μs and is terminated by a rapid fall-off (of about the same duration as that of the rise time). Group a signals are frequently followed by group b signals after a time interval of several hundreds of microseconds. This occurrence is called an 'a–b pair'. If a group b signal has not been detected within this time, then a group a or b signal appears after a time period ranging between 0.2 and 2s. Sometimes a string of several group a signals appears and is followed by a group b signal.

3.2. Fractographic examination

Fractographic examination showed that, in addition to glass powder and a network of small cracks (Rossmanith et al. 1997), some large 'chips' were formed. These are large cracks, which originated at some depth and propagated until reaching the surface of the sample. Their observed fracture areas varied between 1 and 30 cm².
As shown by Goldbaum et al. (2001), the group a pulses are excited by the creation of these flakes. In this paper we present arguments that show that the group b pulses are derived from a polarization process.

3.3. Brief theoretical consideration

The measured quantity in our experiments is the electromotive force in the loop antenna, which is given by $V = -\Phi/\Phi$, the time derivative of the magnetic flux $\Phi = \int B \mathrm{d}S = BS$. Here $B$ is the magnetic induction through the antenna and $S$ is its constant area. Since the apparatus sampling time is $2 \times 10^{-8}$ s, while $r/c \approx 10^{-10}$ s, the latter can be neglected in comparison and we have (Bleaney and Bleaney 1965)

$$B = \frac{\mu_0 I \sin \theta}{4\pi r^2} - \frac{\mu_0 I \sin \theta}{4\pi cr},$$

$$\frac{\mathrm{d}B}{\mathrm{d}t} = \frac{\mu_0 I \sin \theta}{4\pi r^2} - \frac{\mu_0 I \sin \theta}{4\pi cr},$$

where $\mu_0$ is the magnetic constant, $c$ is the speed of light, $l$ is the length of the element in which current is present, $r$ is the distance between the antenna and the current, $I = I(t)$ is the current, the angle $\theta$ is created by the current direction and the radius vector to the antenna relative to the current, and a dot denotes time differentiation.
Since our experiments were carried out in the so-called ‘short’ zone, we can neglect the second terms in equations (1 a) and (1 b) and write

$$V = -S \frac{dB}{dt} = -\frac{S\mu_0 l \sin \theta}{4\pi} \frac{\dot{I}}{r^2}. \quad (2)$$

Consider now a changing dipole \( p(t) \) with a constant length \( l \) and changing charge \( q(t) \): \( p(t) = lq(t) \). The current (Bleaney and Bleaney 1965) is \( I = dq/dt \), \( \dot{I} = dp/dt \), and

$$\ddot{I} = \frac{d^2 p}{dt^2} = \ddot{p}. \quad (3)$$

Thus, the electromotive force \( V \) in the antenna is proportional to the second derivative of the dipole moment:

$$V = -\frac{S\mu_0}{4\pi r^2} \ddot{p}. \quad (4)$$

If instead of a dipole moment one considers the sample’s polarization \( P \), which is defined as its dipole moment per unit volume, the electromotive force would be proportional to the second derivative of the polarization:

$$V = -\frac{\ddot{P}}{C}. \quad (5)$$

Here \( 1/C > 0 \) is the proportionality constant. The polarization current is given by the integral of equation (5):

$$\dot{P}(t) = \dot{P}_0 - \int_0^t CV(t') \, dt'.$$  

where \( \dot{P}_0 \) is a constant, and the polarization \( P \) is given by the integral of equation (6):

$$P(t) = P_0 + \int_0^t \dot{P}(t') \, dt'.$$  

3.4. Examination of group b signals

We assume that the group b signals (figure 1(c)) originate from a change in material polarization (equation (5)). By equation (6), the first integral of the signal should be proportional to \( \dot{P} \), while the second integral should be proportional to the polarization \( P \) itself. This sequence is schematically shown in figure 3. A smoothed group-b-like signal is shown in figure 3(c), while its first and second integrals appear in figures 3(b) and (a) respectively.

Ogawa et al. (1985) measured EMR with an electric sensor. Hence the signals obtained by them (see figures 2 and 3 of the paper by Ogawa et al. (1985), redrawn here as figures 4(a) and (b)) should be proportional to the depolarization current, or to the first derivative of the polarization; and the time derivative of their signal (figure 4(c)) should be proportional to \( \ddot{P} \).

Comparing the pulse shown by Ogawa et al. ((1985) in figure 3 of their paper redrawn here as figure 4(b)) with the integral of a group b pulse (figure 3(b)), it is clear that they are very similar, indicating that both stem from a similar process, namely polarization changes. The shape of the polarization itself can be obtained by the appropriate integrals.
3.5. Hole depths at which group a pulses originate, and crack surface areas

Hole depths where the group a signals originate were estimated by assuming that the drill bit advanced with a constant velocity (the total hole depth divided by the total drilling time) and that the pulse was emitted from the same depth reached by the drill bit at the moment. Crack areas were measured by flake dimensions (length and width) and compared with values of the ratio $T'/\omega$ (see below).

Measured crack (flake) depths, and appearance times of the corresponding group a signals showed a good coincidence. We could thus match definite group a pulses to definite cracks: for each of samples 2 and 3, only one flake occurred, and each emitted a single group a pulse. In each of the remaining three samples, several flakes appeared. In samples 4 and 5, each flake emitted a single pulse. From all other flakes, several pulses were emitted, implying that they fractured in several stages, that is the fracture decelerated or even stopped and then reaccelerated.

For group a pulses the ratio $T'/\omega$ was calculated. It should be proportional (see §1, item (iii)) to the area of the crack. The directly measured crack areas are indeed seen to be proportional to the $T'/\omega$ ratios (figure 5). The proportionality coefficient $\alpha$ is $(7.3 \pm 1.2) \times 10^{-9}$ cm$^2$ s$^{-2}$. The spread of points in the graph is probably due to different crack propagation velocities for different cracks.

3.6. The polarization model

The emerging picture of the process is as follows. During drilling, a stress–strain field is slowly accumulated in the sample by numerous accumulated impacts,
Figure 5. The ratio $T'/\omega$ versus observed crack area, with the linear fit: the proportionality coefficient $\alpha$ is $(7.3 \pm 1.2) \times 10^{-9}$ and $R^2 = 0.83$.

followed by an increase in polarization (Varotsos et al. 1999) (see figure 3(a) for the final stage of this process). This accumulation of stress and polarization can take place only sufficiently ahead of the drill bit, since the region close to the latter is reached by it before the stress grows sufficiently. During polarization increase, $p$ is too small to be detected (figure 3(c)). Note that electric polarization (i.e. the appearance of a dipole moment in a material) can be caused (Rzhesvskii and Novik 1978, Khesin et al. 1996, 1997) by four basic processes: electronic, ionic, dipolar and space charge polarization. Since relaxation times of the first three processes are less than $10^{-6}$s, and since measured relaxation times for glass polarization are of the order of 10 s (Kuksenko et al. 1997), the process here can only be due to space-charge polarization.

Crack development begins when the accumulated stress becomes sufficiently large. Crack propagation (indicated in our measurement by a group a signal) is accompanied by stress relaxation, and the latter causes depolarization and the appearance of a group b signal. That is the reason why group a signals are followed by group b signals, within a small time interval. Natural polarization relaxation in glass is very slow (see above) and can therefore be neglected.

However, polarization does not fall off at once, because not all ions participating in the depolarization current begin their movement at the same moment; an ion begins to move when the acoustic waves excited by fracture reach it.

The time that it takes a crack to travel through the entire sample whose size is 10 cm (with a velocity of 300 m s$^{-1}$, which is low but possible in glass) is 300 $\mu$s. We have registered 33 couples in which group a signals were followed by group b signals, and 12 of these have a time lag of less than 300 $\mu$s (figure 6). There are seven couples with a time difference between the group a and b pulses of up to 600 $\mu$s. These longer times may be due to the fact that not all ions are situated in the way of the propagating crack. Some of them are placed at rather large distances from the crack; so stress relaxation must first reach a definite point on the crack route and then be transferred by acoustic waves to the distant ions. For larger measured differences it is assumed that there was an additional signal in between those observed that has not been detected by our equipment possibly because of very small solid angle at the antenna.
Figure 6. Distribution histogram of time lags between a group a signal and a following group b signal.

Figure 7. (a), (b) Schematic diagrams of slight differences in depolarization shapes. (c), (d) These can cause large shifts in the time lags between the observed signal pair.

Note that the spread in the histogram (figure 6) can also be due to another reason. To understand this, let us consider figures 7(a) and (b) that schematically show two examples of possible depolarization events. The calculated group b signals (second derivatives) (figures 7(c) and (d)) show that the second signal (figure 7(d)) is
shifted by 10 time units with respect to the first signal (figure 7(c)). This means that a negligibly small change in the depolarization shape may cause a significant shift in the group b signal origin, and hence to a spread of delay times between the group a and the b signals.

Flake cracking induced by the drill bit thus leads to the measurement of a group b signal. When cracking stops, stress relaxation and depolarization current increase also halt. Thus 'immediate' depolarization can be incomplete and some polarization could still remain in the material. The latter continues to decrease rather slowly to zero (figure 3(a)). The depolarization current (figure 3(b)) generally changes too slowly to give a measurable second derivative (figure 3(c)), but in some pulses a 'tail' appears (figure 8(a), arrow). Since measurements were carried out only up to $1.3 \times 10^{-3}$ s, we artificially continued this 'tail' (for the specific pulse of figure 8(a)) and evaluated its first and second integrals (figures 8(b) and (c)). Note that the derivative of the pulse obtained by Ogawa et al. (1985) (figure 4(c)) shows a similar 'tail'.

The estimated decay (relaxation) time for such a 'tail' is several milliseconds, which is much shorter than the approximately 10 s relaxation times observed in glass (Kuksenko et al. 1997). This decay time decrease can be due to material heating. It was shown (Kuksenko et al. 1997) that the EMR pulse decay time decreases significantly with a rise in temperature. Measurements of temperature rise during fracture have been carried out for different materials, yielding very high values. For instance, for PMMA the temperature increase was about 500°C (Swallowe et al. 1986), while for glass it was about 840°C for a 200 m s$^{-1}$ crack velocity (Li et al. 1988).
Comparison of the general shape and value of the rise–fall times of group b pulses enables us to assume that these pulses are excited by space-charge polarization (Rzhevskii and Novik 1978, Gueguen and Palciauskas 1994). The charge carriers causing polarization are probably the weakly pinned Na⁺ ions (Kuksenko et al. 1997) of the glass. Hovestadt (1902) described a change in the position of temperature markers on a thermometer over time. A structural change in a silicate mineral (feldspar) at room temperature was ascribed to a Na⁺ displacement under strain (Bahat 1968). These relatively heavy, weakly bound ions (Babcock 1977) can leave their equilibrium positions and move under stress, leading to polarization. When stress is removed or relaxed, these ions return to their equilibrium positions.

One remark is in order. The high-frequency ‘decorations’ of both the group a and the group b signals are evidently due to the powder and small cracks generated by the drill simultaneously with the flaking and depolarization process discussed here.

Summarizing, we found the following.

1. The polarization process is caused by stress–strain accumulation from numerous impacts. This is a ‘very slow’ process and is presumably not registered by the measuring equipment.

2. Depolarization starts when the drill bit approaches the region of the polarized atoms, and the stress is sufficient for crack (flake) creation. The flake creation process itself is accompanied by a group a pulse, while the depolarization process is accompanied by a group b signal. As the latter is fast enough it is recorded by our equipment.

The flake–depolarization pairs should occur in a cyclic manner since, following depolarization, it takes some time for a repolarization process ahead of the drill bit to recur. Hence also the emission of a–b signals should be cyclic and not continuous. However, since following the first a–b pair creation the stress does not fall off to zero, it should take less time for the stress to increase to the critical value than the time to build up the first group b pulse. This phenomenon was actually observed as a gradual decrease in the time periods between pairs.

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