Directional crack propagation in drying process of wet granules

T.Mizuguchi and A.Nishimoto
Department of Physics, Kyoto University, Kyoto 606-8502, JAPAN
S.Kitsunezaki
Department of Physics, Nara Women's University, Nara 630-8506, JAPAN
Y.Yamazaki
Institute for Nonlinear Sciences and Applied Mathematics,
Hiroshima University, Higashi-Hiroshima 739-8526, JAPAN
I.Aoki
LFMI, NINDS, NIH, USA

ABSTRACT: Pattern formation phenomena of crack observed in drying process of wet granular materials are investigated. With some combination of granular material and liquid, nonuniform shrinkage induced by drying process causes crack formation of bulk sample in several ways. Especially, directional crack propagation and columnar structure formation are observed in the experiments. Measurement of water content distribution during drying process shows an existence of front at which crack tips locate.

1 INTRODUCTION

The study about crack pattern is old topics for engineering and physics. The elementary process is, however, fracture which is highly nonlinear phenomena and is not well understood from theoretical and experimental view (Walker 1986). Mud crack shown in tidal land is considered to be made by non-uniform volume change when it dries. As the simplest experiments, mixture of granular material and liquid in a container shows pattern formation of cracks during drying process (Groisman 1994). Recently, Müller reported two types of cracks and that columnar structure with polygonal cross section is formed with starch-water mixture(Müller 1998a; Müller 1998b). They analyzed the final crack pattern using X ray tomography and discussed the relationship between the structure observed in basalt columns and them. We used the same combination of materials and found the columnar structure, independently.

In this letter, we report experimental results of crack formation process of starch-water mixture of drying process. In Section 2, static patterns observed in thin and thick sample after drying process is introduced. Dynamical behavior of water content distribution is shown in Section 3.

2 STATIC PATTERNS

2.1 Setup

Mixture of granular material(starch) and liquid(water) is poured into the container which upper side is left open and is settled into constant temperature and humidity environment. During drying process, the mixture starts to shrink and cracks emerge and form patterns. When the water content of mixture equilibrated with the environment, the drying process and the development of cracks finished. The dominant factor of the experiments are the species of granular material and liquid, depth of mixture, the surface condition of container, temperature and humidity. We perform experiments with changing the depth of sample to see the depth dependencies of crack pattern.

2.2 Thin case

The mixture consists of corn starch (50g) and distilled water (50g) and the container is glass Petri dish (160mm diameter) settled in air conditioned room (temperature: $\sim$ 20 °C and humidity: $\sim$ 35%). The depth of sample is about 5mm. Crack pattern was recored by the video camera from the above and analyzed by the computer.

Typically, in the first one or two days (depending on the conditions) no crack is observed. After that, straight cracks run sequentially and make cellular patterns. Later, another kind of cracks which is more sinuous compared with the straight one emerges. We named the former and the latter type 1 and type 2, respectively.

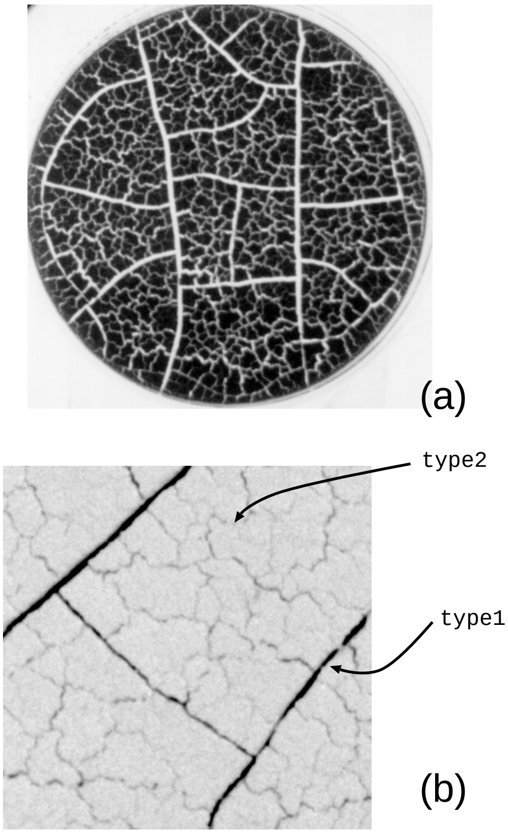

Figure 1: Crack pattern of thin sample. (a) Long shot with transparent light and (b) close-up (25mm×25mm) with reflected light. Two kinds of cracks, type 1 and type 2, are observed. The former is smooth and the latter is sinuous.

Figure 1 shows typical pattern and its close up from above. By comparing with the image by transparent light and reflected one, it becomes clear that type 1 has no three dimensional structure while type 2 evolves and the crack network changes its shape along vertical direction (, i.e. z axis). In most cases with other granular materials, e.g., magnesium carbonate, only type 1 is typically observed. Within our trials, type 2 crack is observed only with starches. About type 1, the formation mechanism of crack and morphology is well studied(Groisman 1994; Kitsunezaki 1999; Leung 1997). For example, the average cell area divided by type 1 crack is proportional to square of sample height. Type 1 is produced by the stress concentration comes from the difference of contraction ratio between mixture and container and the friction between them.

We focus on the structure and dynamical behavior of type 2 crack, and therefore use deeper sample in order to eliminate the type 1 crack in the next experiments.

Figure 2: Thick sample (broken manually). Sample height is 50 mm.

2.3 Thick case

The setup of experiments is changed geometrically, i.e., the depth of sample is 20mm or deeper. And to suppress the adhesive effect with side walls, Teflon beaker is used. The temperature is controlled to 40±2°C by thermostat.

Figure 2 shows typical thick sample, broken manually after drying process to see its internal columnar structure. To observe their cross sections in detail, the sample is solidified by epoxy resin containing dye. By cutting off the surface with lathe, horizontal and vertical cross sections can be recorded by video camera or optical scanner. Figures 3 show typical vertical and horizontal sections.

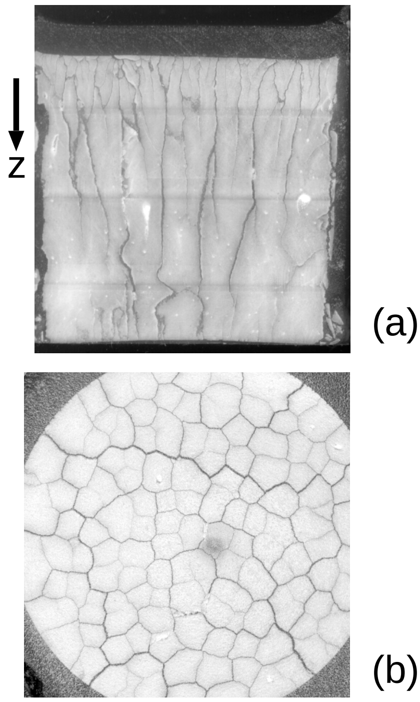

Figure 3: (a) Vertical section parallel to the z axis. Sample size 20mm×25mm. (b) Horizontal cross section at 11.6mm depth from the surface. Diameter of sample is 40mm.

Vertical section shows that columnar structure is recognized and their size fats along z axis. Horizontal section clearly indicates polygonal structure. The polygons are not completely regular and there exist cracks which end at single hand vertex. By scraping off the surface gradually, a set of continuous cross sections along z axis is given. The network of cracks change its shape along z axis by reconnection process.

As a quantity which characterizes crack patterns, we measure total crack length L by digitizing and thinning the images at each depth. Figure 4 shows depth dependency of L. It is clear that L decreases (and average size of columnar increases) to some depth. The two short lines in fig. 4 show thinner samples (10mm). The coincidence of the four line near the surface insists that L depends not on the sample thickness but on the distance from the surface. The reason for increase of L at lower part may account for another crack front comes from bottom and side.

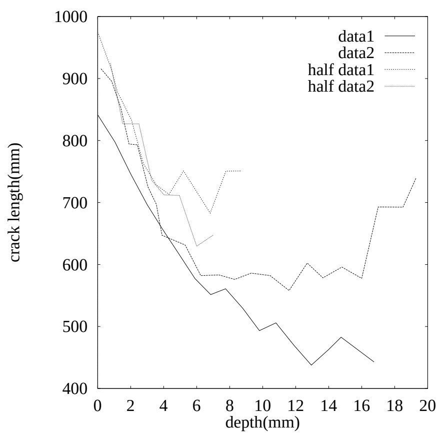

Figure 4: Depth dependency of total crack length L. Sample height is 20mm for data1 and 2, and is 10mm for half data1 and 2.

These results suggest that type 2 crack is made by stress concentration due to the local shrinkage by water evaporation process from the surface. In the next section, we observe spatial distribution of water content of samples during drying to confirm it.

3 DYNAMICAL BEHAVIOR

3.1 Setup

To observe the dynamical behavior of cracking process, the sample is settled in MRI instruments with constant temperature. The initial sample size is 28.5mm diameter × 27mm height. Spatial distribution of water of sample is measured continuously during drying.

3.2 Results

Figures 5 show snapshots of water distribution of one sample at 71 hours later from starting of drying process. Figure 5(a) is a vertical cross section and (b),(c) and (d) are horizontal cross sections at

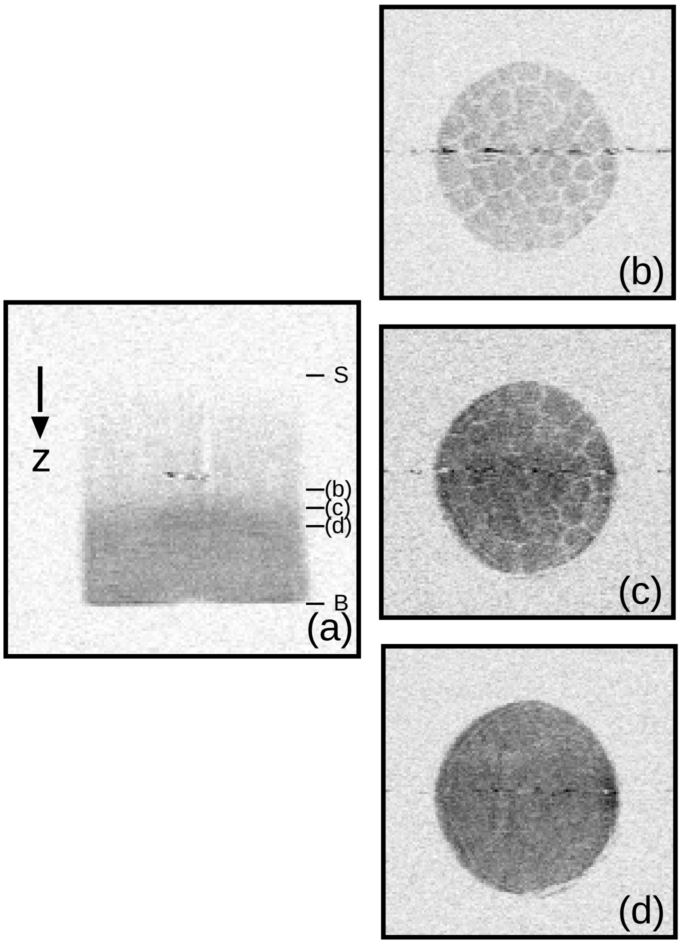

Figure 5: (a) Vertical and (b)(c)(d) horizontal sections during drying. Gray scale represents local water content. In (a), "S" and "B" denote the position of the surface and the bottom, respectively. "(b)","(c)" and "(d)"indicate the position of horizontal sections corresponding figures in right column.

13 mm, 11 mm and 9 mm from the bottom, respectively. Figure 5(a) indicates that the lower part of sample is wet while the upper part is rather dried and a front of water content is recognized around 11 mm depth. From figures 5(b),(c) and (d), polygonal structure emerges at the front between wet and dried region and well developed above the front. As drying process goes, the water content front sweeps the sample downward. The position of water content front and of emergence of polygonal structure is well coincide with each other during drying process. These observations insist that type 2 crack is induced by stress concentration due to water content front.

4 CONCLUSIONS

In this letter, we study the structure and dynamics of type 2 cracks observed in starch-water mixture and water content distribution. It is concluded that crack fronts move together with water content front (or "shock"). Even in porous media, derivative of water distribution becomes smooth with depth (and time) for drying process. This result is qualitatively consistent with the z dependency of L (or columnar size) because stress concentration is considered to be proportional to the gradient of local volume change.

Related and fascinating phenomena of crack propagation due to "shock" is columnar structure of basalt in geology (Folley 1694), however, its beautiful structure and dynamics are not fully understood up to this time(Lachenbruch 1962; Aydin 1988; Hsui 1989). There are some other examples of crack propagation due to thermal shock for glass (Bahr et al. 1996; Yuse 1997; Ronsin 1997) or ceramics(Korneta et al. 1998). They discussed the depth dependencies of interval of cracks for two dimensional cases. Extensions for three dimensional systems is required.

Investigations about such crack formation processes are starting(Leung 2000). Further detail studies, such as rheological and/or porous properties, may clear necessary conditions to form type 2 crack.

REFERENCES

Aydin, A. & Degraff, J. (1988). Evolution of polygonal fracture patterns in lava flows. Science 239, 471.

Bahr, H.-A. et al. (1996). Fracture mechanical analysis of morphological transitions in thermal shock cracking. Fracture Mechanics of Ceramics 11, 507.

Folley, S. (1694). An account of the giant causway in the north of ireland. Philos.Transact. (212), 170.

Groisman, A. & Kaplan, E. (1994). An experimental study of cracking induced by desiccation. Europhysics Letters 25(6), 415.

Hsui, A. (1989). Possible consequences of a fluid dynamic origin for columnar joints in basalts. Archs.Sci.Geneve 42, 425.

Kitsunezaki, S. (1999). Fracture patterns induced by desiccation in a thin layer. Physical Review E 60(6), 6449.

Korneta, W. et al. (1998). Topological and geometrical properties of crack patterns produced by the thermal shock in ceramics. Physical Review E 57(3), 3142.

Lachenbruch, A. (1962). Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost. Spec.Pap.Geol.Soc.Am. 70, 69.

Leung, K. & Andersen, J. (1997). Phase transition in a spring-block model of surface fracture. Europhys.Lett. 38, 589.

Leung, K. & Neda, Z. (2000). Pattern formation and selection in quasi-static fracture. Phys.Rev.Lett 85, 662.

Müller, G. (1998a). Experimental simulation of basalt columns. J. Volcanology and Geothermal Research 86, 93.

Müller, G. (1998b). Starch columns: Analog model for basalt columns. J. Geophys. Res. 103(B7), 15239.

Ronsin, O. & Perrin, B. (1997). Multi-fracture propagation in a directional crack growth experiment. Europhys. Lett. 38, 435.

Walker, J. (1986). Cracks in a surface look intricately random but actually develop rather systematically. Sci. Am. 255, 178.

Yuse, A. & Sano, M. (1997). Instabilities of quasi-static crack patterns in quenched glass plates. Physica D 108, 365.